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Advanced planning methodologies in food supply chains

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DTU Management Engineering
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Advanced planning methodologies in food supply chains

PhD thesis by Poorya Farahani

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Advanced planning methodologies in food supply chains

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Preface

This dissertation is submitted to DTU Management Engineering, Technical University of Denmark, in partial fulfilment 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 September 2007 to February 2011. The papers included in this thesis have been updated to the most recent version available from the respective journal review processes.

Poorya Farahani, Kgs. Lyngby, Denmark, February 2011

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The members of the Operations Management group have significantly contributed to my personal and professional time at DTU. During my stay at the Operations Management group I experienced a very friendly as well as collaborative environment. I would like to thank my fellow PhD researchers, Yang Wang, Klaus Reinholdt Nyhuus Hansen, Thordis Anna Oddsdottir and Line Reinhardt for supporting me during my PhD project. My special thanks go to Christina Scheel Christiansen for her continuous support with all the administrative processes of my PhD project, and her positive spiritual contribution which made my stay at the Operations Management group a happy experience.

I am honored for the opportunity of spending six months of my PhD project doing research collaboration with the Productions Management group of Technische Universität Berlin. I am deeply grateful for the great support and the priceless advice I received from Professor Hans-Otto Günther during my stay at TU Berlin. Not only was he readily available for me, but he always read and responded to the drafts of my work more quickly than I could have hoped. Also thanks to my colleagues at TU Berlin, Rico Gujjula, Mario Lueb and Andreas Schöpperl who made my time in TU Berlin enjoyable as well as productive.

My academic achievements would not have been the same without the immense support of friends and family. Thanks to all my friends in the sports club of DTU who contributed a lot in enriching the social aspect of my life at Copenhagen, and provided me with a relaxed environment, especially when the work was getting stressful. Thanks also to one of my best friends, Moein Rezazadeh, for inspiring and encouraging me to pursue my education to the highest levels.

To my parents: Thank you for giving me the freedom and chance to pursue my own interests, even when they seem dangerous and incomprehensible. I particularly thank my mother for her spiritual support of my long-term decisions, even when they were in contradiction to her desires, and my father for teaching me that there is no limit to progress for he who wants success.

Contents

Abstract

The food industry is an important sector both because of its direct impacts on the daily lives of people and its large share of Gross Domestic Product (GDP) compared with other economic sectors. This thesis discusses and develops advanced planning methodologies to optimize operations in food supply chains. From a supply chain perspective, this thesis mainly focuses on the part of the chain which starts from the food processing industry: the food processing industry, the distribution industry, and final consumers. In the second chapter of this thesis, a thorough review is presented classifying the related contributions in strategic, tactical, and operational studies, aiming to explain how several key food distribution planning challenges have been dealt with in the Operations Management literature. The next two chapters discuss specific production and distribution planning problems from the foodservice sector. Generic mathematical models are developed, which represent the main characteristics of this industry, including product quality considerations. The models are solved through tailor-made algorithms and managerial insights based on numerical results are discussed. The last chapter of the thesis summarizes the scientific and managerial conclusions of the research project and outlines the future research directions.

Resumé

Fødevareindustrien er en vigtig sektor, både fordi den har direkte indflydelse på folks dagligdag og fordi den udgør en stor andel af bruttonationalproduktet sammenlignet med andre økonomiske sektorer. Denne afhandling diskuterer og udvikler avancerede planlægningsmetoder til optimering af driften i fødevareforsyningskæder. Ud fra et kæde-synspunkt fokuserer afhandlingen primært på den del af kæden, der begynder i fødevareforarbejdningsindustrien: fødevare-forarbejdningsindustrien, distributionssektoren og de endelige forbrugere. I andet kapitel af afhandlingen foretages en grundig gennemgang og klassificering af de relaterede bidrag i strategiske, taktiske og operationelle studier. Dette er et forsøg på at forklare, hvordan man i den eksisterende litteratur om Operations Management har beskæftiget sig med flere af de væsentligste udfordringer inden for distributionsplanlægning i fødevaresektoren. De efterfølgende to kapitler diskuterer specifikke produktions- og distributionsplanlægningsproblemer inden for catering-sektoren. Der er udviklet generiske matematiske modeller, som repræsenterer de væsentligste karakteristika ved denne industri, inklusiv produktkvaliteten. Modellerne løses gennem skræddersyede algoritmer, og ledelsesmæssige forståelser baseret på numeriske resultater diskuteres. Det sidste kapitel i afhandlingen opsummerer de videnskabelige og ledelsesmæssige bidrag, der kan uddrages af forskningsprojektet samt udstikker retningslinjerne for den fremtidige forskning.

Chapter 1. Introduction

The Food industry is an important sector with direct impacts on the daily life of the entire population of a society. Accounting for 8% of total EU GDP (International Monetary Fund (IMF), Eurostat, 2006), the food and drink industry also represents an important economic sector. The food supply chain involves all industries collaborating to provide final consumers with foods. The scope of food supply chain stretches from farms, as the first origins of food products, to fork (consumer), as the last point of consumption. Thus, it connects the following three industries in a supply chain context: the agriculture and farming industries as raw materials providers; the food processing industry which transforms raw materials into finished products, and the distribution industry which carries out the logistical responsibilities. Figure 1 provides a general structure of food supply chains. However, it is not necessary for all components shown in figure 1 to be available in every food supply chain.

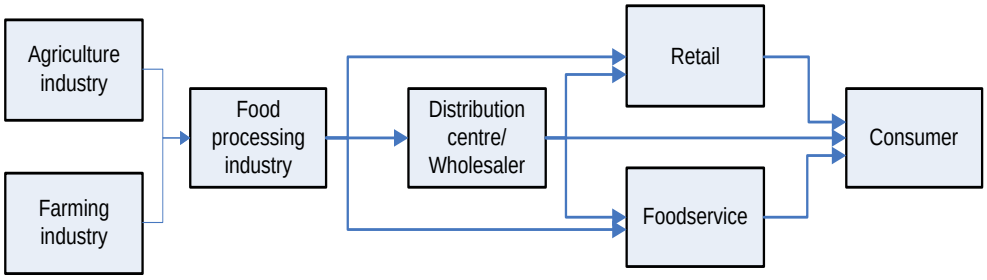

Figure 1. General structure of the food supply chain.

1.1 Classification of food supply chains: foodservice/catering vs. retail chains*

Food supply chains can be classified as foodservice/catering chains or retail chains depending on the type of customers and the way food is prepared and delivered to customers. Eastham et al. (2001) distinguish retail and foodservice from a consumer perspective, based on whether the food is consumed inside or outside a hospitality service provider. Though fuzzy, this definition establishes a common ground for classifying many of the available food supply chains. Other characteristics, e.g., outlet dispersion, supply volumes and the use of technological systems like Electronic Data Interchange (EDI) or Electronic Point of Sale (EPoS) further differentiates the two sectors.

Foodservice/catering chains include all undertakings involved with the provision of prepared foods ready for consumption away from home, and the food delivery service to be consumed at home, with food preparation taking place elsewhere. Catering chain has a complex network which provides prepared, and in a lot of cases hot, meals for immediate consumption to a broad range of customers including hotels, cafes, take-aways, restaurant, hospitals, nursing homes, schools and

* Based on Chapter 2.1.1 of Akkerman et al. (2010)

kindergartens (Taylor 2008). Foodservice industry is dominated by SMEs (small- and medium-sized enterprises), and often small-scale production units. However, the increasing number of elderly people, and the number of one person households and the rising share of out-of-home dining imply a growth in the size of foodservice industry (Buckley et al. 2007). The possibility of storing prepared foods is often very limited in foodservice industry due to the fast quality degradation. Therefore, one of the main challenges of this industry is to ensure quality delivery through appropriately integrating production operations with distribution.

Unlike the catering industry, the retail industry has seen a significant consolidation and is dominated by large retailers (Dobson et al. 2001). For instance, retail chains like Netto, Sainsburry and Tesco are some of the dominating actors in this market. Compared to the catering industry where products are usually produced for immediate consumption, the retail industry often provides a wide variety of products, which in a lot of cases can be stored for a significant amount of time before being picked up and consumed by a customer. An important concern in retail chains is to effectively use the massive volume of available data through industry initiatives like efficient consumer response (ECR), aiming to improve the efficiency in the collaboration between producer, distributor and retailer. This is often achieved through creating a pull distribution system, based on an IT system that relies on EPoS data (Hoffman and Mehra 2000). Furthermore, the growth of online retailing in recent years (Boyer and Hult 2005) has led to emergence of different distribution channels, such as direct shipment from producers to consumers (Agatz et al. 2008). Respectively, there is special attention towards determining, e.g., appropriate pricing schemes for different distribution channels.

1.2 Food supply chain planning challenges[†]

Respecting safety standards, securing desired food quality, and improving sustainability measures are the most crucial challenges in planning operations of food supply chains. These issues are dominating the current debate in the society with respect to the food sector, demonstrated by extended coverage in newspapers and trade journals. In response to these challenges and due to the special importance of food in people's daily life, several initiatives and governmental and international regulations about the production and distribution of food products have been developed during the last decade. Following, each of these challenges is briefly discussed through introducing some of their relevant developments and legislations.

1.2.1 Safety

Food safety generally refers to the prevention of illnesses resulting from the consumption of contaminated food. The increasing attention of the industry for food safety is partly due to the fact that much legislation has been enforced on this matter, but it also has an economical motivation: food safety (or related information) can be a competitive factor, and more importantly, the implications of a major food safety failure can be commercially devastating. This includes product

[†] Based on section 2.3 of Akkerman et al. (2010)

recalls, damage to reputation and punitive liability damages (Hobbs 2006). A well-known example of such a food safety crisis is the recent recall of peanut butter in the USA due to the presence of salmonella. It was the largest product recall ever in the country's history, involving more than 200 food manufacturers downstream in the supply chain – in total recalling more than 2100 products (Terreri, 2009).

After the realisation of some food safety crises, e.g., the BSE crisis in the 1990s, different international organisations have effectively been engaged in re-evaluating and developing risk assessment and risk management systems for food safety. Accordingly, efforts have been exerted into, e.g., effective implementation of HACCP concept (FAO 2003) and the ISO 22000 standard (ISO 2005) to guarantee food safety mainly during the production and processing stages. In addition, governments are imposing new legislations that enforces traceability of food products during all stages of production, processing, and distribution (e.g. European Parliament and Council, 2002). For instance, more strict rules have been developed in the last decade for appropriately labelling food products throughout the supply chain so that the unsafe and low quality products can be more easily and more quickly identified and called back from stores. Despite the importance of traceability, the reality is that in complex, interconnected food supply chains, complete traceability is more the exception than the rule (Miller, 2009). Schwägele (2005) argues that traceability has to be in food companies' interest, and not just seen as legislation that has to be followed. Some recent literature follows this by discussing how the introduction of traceability might actually be used to add value to a company's operations (Wang *et al.*, 2009a).

1.2.2 Quality

Securing acceptable level of food quality for customers has also become a major concern. As noted by Grunert (2005), food quality usually refers not only to the physical properties of food products, but also to the way the product is perceived by the final consumer. This can for instance include microbial aspects, but also texture or flavour. Due to the importance of product quality in the food industry, Trienekens and Zuurbier (2008) expect that quality assurance will dominate the process of production and distribution, and that the costs for certification, auditing and quality assurance may evoke responses like technological innovation to create higher efficiency and reduce costs. New technological developments also allows for improved shelf life estimation with a chain perspective, as is for example shown by Raab et al. (2008) for pork and poultry chains and Dalgaard et al. (2002) for fish chains.

In the foodservice sector, the culinary quality of meals is a much debated issue throughout Europe (e.g. Mikkelsen et al. 2007; Hartwell et al. 2006; Wright et al. 2006), and is especially relevant considering the expected increase in consumption of professionally prepared meals. Also, in one of the latest developments to guarantee quality of food products to consumers and a fair price for farmers, a new "Quality Package" is adopted by the Agriculture and Rural Development committee of the European Commission in 2010 which, focusing on agriculture industry, defines a new agricultural product quality schemes regulation and new guidelines on product labelling rules (Commission Press Release, IP/10/1692).

1.2.3 Sustainability

Over the past years, sustainability has gained increasing importance in the food industry (e.g. Mattson and Sonesson 2003). Sustainability commonly refers to how the needs of the present human generation can be met without compromising the ability of future generations to meet their needs (WCED 1987). It is increasingly evident that market and regulatory sustainability drivers shape the organization and operation of supply chains. Food supply chains are at the forefront of this development (e.g. Wognum et al. 2010; Vasileiou and Morris 2006). Next to commonly used cost-based performance measures, sustainability includes environmental aspects as well as a social dimension (Kleindorfer et al. 2005). This entails, for instance employees' health and safety, ethical trading in procurement of raw materials, and animal welfare.

The environmental dimension of sustainability has probably received the most attention. One of the best-known examples is Life Cycle Assessment, an analytical tool that helps in assessing a product's environmental impact from product development to consumption (Hauschild et al. 2005). Also, a legislation is under processing that would set legally binding targets for CO2 emissions from EU member states for the year 2050, and possibly for intermediate years. Among other industry, this legislation will also significantly impact the non-sustainable production and distribution of food products in EU countries.

Promoting social and environmental awareness can be beneficial for a corporate image (Chinander 2001), and in some occasions it might lead to cost savings at the same time, for instance while reducing food waste. Numerous companies have started to work on the social dimension of sustainability under the label 'Corporate Social Responsibility' (CSR). In many cases they also communicate their CSR performance to stakeholders like employees or customers. For instance, all ten major retailers in the UK have stated that they see CSR as an integral element of their business environment, although there are substantial variations in the nature and extent of the CSR information they provide (Jones et al. 2005).

Next to the direct impacts retailers and caterers have on sustainability, sourcing sustainable products from food manufacturers is also of major impact (Baldwin 2009b), also related to CO2 emission, waste and refrigeration related to storage, and foodservice operations during preparation and service (Turenne 2009). A well-known concept in relation to the sourcing and the sustainability of food chains is that of labeling, for example in the form of food miles, which relates to the distance a food product has travelled to get to the consumer. Although this only partially reflects the carbon footprint or even total environmental impact of the production and distribution system, the concept has become relatively popular (Saunders et al. 2006; Wilson 2007).

Chapman (2010) states that around 30% of food products is said to be wasted throughout the supply chain, highlighting the importance of food waste reduction aspect of sustainability. Also, a report released by the Confederation of the Food and Drink Industries of the EU in November 2010 states that the annual food waste across Europe is approximately 89 million tonnes. Even though a large part of this waste occurs at the final consumer, the production, storing and distribution operations also contribute significantly. This implies that the raw materials, production and

distribution resources used in preparing the wasted foods are also wasted, resulting in a significant inefficiency of food supply chain operations.

The three introduced topics of food safety, quality and sustainability are also strongly connected to each other. Nowadays, systems that are originally designed to control food safety (like HACCP) are also used to increase the product quality throughout the supply chain (Panozzo et al. 1999). Also, extending the quality and safety control systems into transparent food chains that are able to supply affordable food with high quality and diversity are some of the challenges related to the sustainability of the food industry (Fritz and Schiefer 2008). The challenge for the industry is, as Smith (2008) stated, to extend responsibility for product quality into social and environmental performance of food supply chains.

1.3 Temperature control: an effective tool to control food quality and safety ‡

Besides the introduced challenges, food supply chains are also very complex in terms of products' requirements. One of the crucial requirements of food products is appropriate control of temperature during different production and distribution stages. Establishing an effective temperature control system remarkably influences both the quality and safety of foods. It affects product quality by influencing the level of quality degradation and affects product safety by influencing the growth of potentially harmful bacteria (such as *Salmonella* and *Escherichia coli*). On the other hand, insufficient temperature control may even lead to chemical reactions that could change a product's appearance or texture. These undesirable changes in product characteristics determine the shelf life of the food product, which is hence often linked to a temperature requirement.

In relation to temperature control, we can basically identify three types of food supply chains: frozen, chilled and ambient. For the frozen and chilled chain, a number of different temperatures are used. The frozen chain mainly operates at -18°C, although a product like ice cream requires a frozen chain with an even lower temperature of -25°C. For the chilled chain, temperatures range from 0°C for fresh fish to 15°C for, e.g. potatoes and bananas (Smith and Sparks 2004). Finally, an ambient chain concerns products that do not require temperature control, such as canned goods. This classification reflects the main modes of handling products in terms of production and distribution technologies, related to temperature control and product packaging, (e.g. cooling equipment or insulating packaging material). It also corresponds to different ways of dealing with quality degradation.

1.4 Advanced planning in food supply chains

In order to meet high customers' expectations and respect the developed legislations, advanced planning methodologies which are traditionally employed in other industries need to be adapted to fulfil the planning requirements of food supply chains. However, in reality, food supply chains often suffer from old and simple planning techniques which have been employed since long times

‡ Based on section 2.1.2 of Akkerman et al. (2010)

ago and have not been updated according to the new needs of this industry. Such lack of advanced planning methodologies in food industry is a natural result of insufficient research on food supply chain planning problems. The literature on planning and coordinating supply chain operations of non-food items is abundant (see for instance Sarmiento and Nagi, 1999; Min and Zhou, 2002; Meixell and Gargeya, 2005; Peidro et. al., 2009; Melo et. al., 2009). Nevertheless, applying planning practices which have been shown to be useful in other fields does not guarantee success in food supply chain planning area. Recently, the research community has started to pay more and more attention to planning challenges in food industry. This is reflected in a growing number of publications about operations planning in the food industry in highly ranked journals.

1.5 Research objectives

The overall aim of this thesis is to contribute to the literature for creating efficient and high-quality food supply. Based on existing theory on general supply chain management, the focus is on the inclusion of the specifics of the food industry to improve the efficiency of the planning methodologies in the food supply chains. For this purpose, it is necessary to combine management and planning methodology with knowledge about food technology and industry. In this thesis, some of the challenges in production and distribution operations of food supply chains are analysed. In contrast to the rather vast body of available literature (refer to Ahumada and Villalobos, 2009) on the initial stage of the food supply chains from agricultural and farming industries to food processing industry, the main focus of this thesis is on food supply chain operations which starts from the food processing industry. Moreover, as will be discussed in Chapter 2, despite the significant challenges in planning its production and distribution operations, the catering sector has not received as much attention in the literature as the retail sector. In response to the lack of research in the catering sector, the scope of this thesis is limited to this industry through selecting the cases from the foodservice/catering chains. Accordingly, the chapters of this thesis are prepared to identify the relevant research gaps and to address some of them through analyzing industry-specific cases.

1.6 Research questions

Although research on food supply chain planning is still in its initial stages, a thorough investigation is necessary to identify how food supply chain planning problems, as discussed in the previous sections, are approached in operations management literature, and how the related literature can be extended to fill the current research gaps. This forms the first research question in this PhD thesis:

RQ1 How are the main challenges of operations planning in food supply chains covered in operations management literature and what are the potential relevant extensions?

Each category of food supply chains, the retail and catering, has certain characteristics and specific challenges which necessitates the development of dedicated planning models. One of the main challenges in the catering sector is that the prepared meals are most often highly perishable,

restricting the possibility of storing them. In such cases, the quality of the prepared meals might dramatically change depending on the storage time and condition. Therefore, appropriate coordination must be established between production and distribution operations. Investigating the influence of such coordination results in our second research question:

RQ2 What are the potential impacts of coordinating production and distribution operations on the total operations costs and the quality of delivered products in the catering sector?

Due to the broad range of skills required to perform the production operations, efficient planning of the workforce is an important and challenging task in the catering sector. In addition, labour is often a major capacity factor to consider in service industries like the foodservice/catering sector. Thus, efficient planning of production operations is directly linked to the selected workforce plan. Although the topic of planning workforce with multiple skills has been researched by many researchers, see for instance Ernst *et al*. (2004) as an extensive review of the literature on this topic, the potential benefits of its integration with production, and respectively distribution planning have not yet been investigated in the catering sector. This leads to the third research question in this thesis:

RQ3 What are the potential benefits of integrating workforce planning with production and distribution operations in the catering sector?

1.7 Thesis outline

In response to the first research question, we present a thorough review on the current status of the literature about food production and distribution planning. There are a few literature reviews (Lowe and Preckel, 2004; Ahumada and Villalobos, 2009) published on food supply chain operations where the principal focus is on the production stages like farming, harvesting and post harvesting operations. Despite the fact that the distribution operations also strongly contribute into food supply chain planning challenges, there was no literature review extensively analyzing how different researchers approach this problem in food supply chains. In response to this need, we did a thorough literature survey by mainly focusing on the research work performed about distribution and joint production-distribution operations in food supply chains. This forms the second chapter of this thesis. The principal characteristics and challenges of food supply chains discussed in the introduction chapter are mainly derived from sections 2.1 and 2.3 of this literature survey paper. Thus, in order to avoid the unnecessary repetition of discussions, Chapter 2 only covers the remaining sections of the review paper.

Industry-specific cases forms the basis of the analyses performed in the other chapters of this thesis. The third chapter is inspired by a Danish catering company which provides lunch for different service organisations and responds to the second research question. We investigated the

effect of coordinating production and distribution operations in this catering company, and showed that an appropriate coordination can lead to significant improvements in the quality of the delivered foods without significantly increasing the total costs. In chapter 4, we analyse the design and operations planning of the institutional meal delivery system in a Danish municipality in relation to the last research question. In this chapter, we develop a hierarchical modelling approach to determine the required workforce jointly decided with the production and distribution plans. Finally, a summary of the results of the previous three chapters is presented and the thesis concludes with indicating the potential future research directions.

1.8 Included publications

1. Akkerman R., Farahani P., Grunow M. (2010), *Quality, safety and sustainability in food distribution: a review of quantitative operations management approaches and challenges*, OR Spectrum 32: 863-904

2. Farahani P., Grunow M., Günther H.-O. (2011), *Integrated production and distribution planning for perishable food products*, under review for Flexible Services and Manufacturing Journal

3. Farahani P., Grunow M., Akkerman R. (2011), *Design and operations planning of municipal meal production and delivery systems*, under review for International Journal of Production Economics

Chapter 2. Literature review

This chapter is based on an article published as:

Akkerman R., Farahani P., Grunow M. (2010), *Quality, safety and sustainability in food distribution: A review of quantitative operations management approaches and challenges*. OR Spectrum 32:863–904.

Abstract

The management of food distribution networks is receiving more and more attention, both in practice and in the scientific literature. In this paper, we review quantitative operations management approaches to food distribution management, and relate this to challenges faced by the industry. Here, our main focus is on three aspects: food quality, food safety, and sustainability. We discuss the literature on three decision levels: strategic network design, tactical network planning and operational transportation planning. For each of these, we survey the research contributions, discuss the state of the art and identify challenges for future research.

2.1 Decision-making processes in distribution management

Managerial decision making is commonly divided into different levels of decision, mainly relating to the time horizon for these decisions (see *e.g.*, Anthony, 1965; Bitran and Tirupati, 1993). This normally leads to the distinction between long-term, mid-term, and short-term planning, or alternatively: strategic, tactical, and operational planning. In this hierarchical approach, we can distinguish three distinct planning levels in distribution management:

- Distribution network design, concerning long-term decisions on the physical distribution structure. This includes *e.g.* the number and sizes of warehouses and cross-docking points, as well as the related transportation links.
- Distribution network planning, concerning mid-term distribution planning decisions related to fulfilling demand (or forecasts) on an aggregate level. This includes *e.g.* aggregate product flows and delivery frequencies.
- Transportation planning, concerning short term planning of the distribution of actual customer orders. This includes *e.g.* the loading and routing of vehicles.

For each of the planning levels, some typical decisions are mentioned in the list above; a more extensive discussion can be found in the remainder of the paper, where the review of literature for each of the levels is introduced by a more detailed discussion of the typical planning problems.

	Planning horizon	Time representation[a]	Objective function(s)	Frequency of analysis[b]
Distribution network design	1-5 years	None, or years	Maximize net revenue or return on assets	Major studies once a year; special studies if needed
Distribution network planning	1-12 months	Days, weeks, months	Minimize total costs of meeting forecasted demand or maximize net revenue by varying product mix	Once a month
Transportation planning	1-30 days	Minutes, hours, days	Minimize myopic distribution costs	Once a day and event-driven rescheduling during the day

Table 2.1. Characteristics of distribution planning on different hierarchical levels (based on Shapiro, 2007).

Planning decisions are typically made based on cost or profit evaluations (Shapiro, 2007). The characteristics of distribution planning on the different hierarchical levels are summarized in Table 2.1. Next to cost- or profit-based objectives, considerations regarding resource utilization, customer responsiveness, or flexibility are sometimes included in the distribution management literature. For detailed discussions of different objectives on the different decision levels, we refer to the recent reviews by *e.g.* Melo *et al.* (2009) and Mula *et al.* (2010). For our review, we will not discuss the objectives of the various contributions unless food-specific aspects are involved.

Not only do the above planning levels relate to different planning decisions and their related planning horizon, but they are also (*i*) strongly related to hierarchical levels in the organization, and (*ii*) distinctly different in terms of the models that are developed and implemented in planning systems to support these decisions. Obviously, some of these differences have to do with how detailed the time aspect is modelled, if included at all. Also, the time distribution managers spend on analysing the solution differs significantly; strategic and tactical decision-making often includes extensive scenario analysis based on the modelling work, while operational decision-making needs quick solutions and the possibility to replan on an ad-hoc basis.

The topics covered in the previous sections (and summarized in Figure 2.1) make up the framework we use in the following sections to review the literature. To keep these tables compact, we used a classification scheme to identify the type of distribution system, which can be either foodservice (S), retail (R), or unspecified (U). Temperature levels can be ambient (A), chilled (C), frozen (F), or unspecified (U). For example, the classification R|CF would refer to a contribution discussing the distribution of chilled and frozen products in the retail sector.

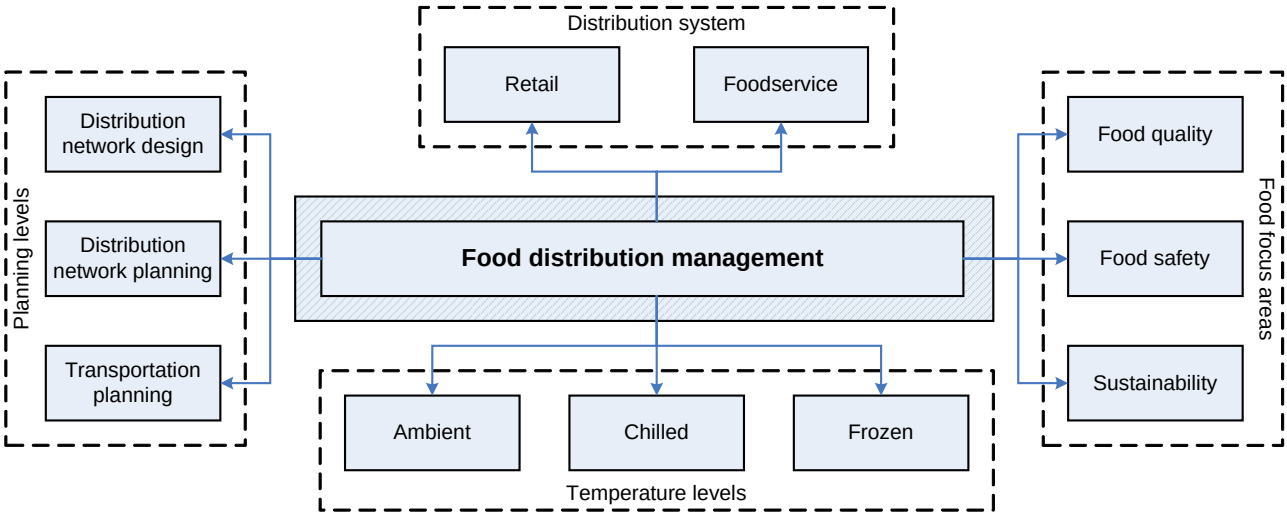

Figure 2.1 Framework used to review the literature on food distribution management.

2.2 Distribution network design

2.2.1 Introduction

Distribution network design concerns long-term decisions on the physical distribution structure of a new network or on the redesign of an existing network. It includes e.g. the location, number and sizes of warehouses and cross-docking points, as well as the related transportation links. Distribution network design is among the most critical operations management decisions facing a firm, as it affects costs, time, and quality of customer service (Jayaraman, 1998).

The main decisions are normally (i) where to locate facilities, and (ii) how to allocate customers to facilities and facilities to each other in case of supply chains with multiple echelons. Together, this is generally referred to as facility location-allocation (Meixell and Gargeya, 2005; Melo et al., 2009).

Typically, the location-allocation problem leads to mixed-integer linear programming models in which binary decision variables are used to decide whether a potential manufacturing plant or potential distribution centre is actually going to be used. Continuous decision variables are used to denote the aggregate product flow in the distribution network ending at the customers where demand has to be fulfilled. Typically, the objective function minimizes the total cost for opening facilities in certain locations, and the production and distribution costs for shipping products through the distribution network (75% according to the review by Melo et al., 2009). Alternatively, profit maximization is used (16%), and to a fairly limited extent other objectives (e.g. robustness, resource utilization, flexibility, and customer responsiveness) are included, but then mostly in addition to financial aspects.

It should be noted that the location-allocation problem is usually described in a basic single-period model. When considering a longer time horizon and multiple periods, the net present values of the included costs have to be used. In today's globalized setting, one might also have to extend this with e.g. exchange rate parameters and different taxation rules (Meixell and Gargeya, 2005).

We refer to Klose and Drexl (2005) for a further discussion on modelling facility location-allocation, with a focus on mixed-integer linear programming approaches. For extensions to the facility location-allocation problem, see for example Cordeau et al. (2006), who also integrate supplier selection, transportation mode selection, and product range assignment. Furthermore, extensions often include more detailed tactical and operational decisions related to the planning of production and inventory and routing decisions (Melo et al., 2009). In Section 2.5, we will provide a more detailed discussion of models integrating different decision levels.

As profit margins can be quite low in the food industry and distribution operations constitute a significant portion of total supply chain costs, great efforts and investments are often put in network design. It is however a challenging task to design food supply chains for products that have good quality, are not expensive and are environmentally friendly (Apaiah et al., 2005). The network design significantly affects the eventual safety of the food product, as the design determines the number of actors, and the extent to which products are dispersed through the network. Regarding product quality, the design of the network influences for example the time a product is subject to quality degradation during distribution. The design of distribution networks has a strong impact on sustainability, for instance related to the distance products have to travel to reach the final consumer, or to the environmental impact of the transportation method involved.

For foodservice chains, the aim is often to pursue a low stock level or a no-stock-overnight policy in distribution centres, and to frequently ship in smaller amounts with high variations in demand. This will often also affect the length of the chain: direct delivery from the producer to the caterer is for instance common for these products (Bourlakis and Weightman, 2004). Another typical aspect found in foodservice systems is that production activities are not always confined to the initial food manufacturing stage, as it is often the case that additional production steps take place at the caterer (e.g. final meal assembly and preparation).

2.2.2 Contributions

Several authors have studied the location-allocation problem for specific food industries using mixed-integer linear programming approaches (cf. Table 2.2). Most of these models include both the locations of production plants and distribution centres. Geoffrion and Graves (1974) provide a general model, which they apply to analyze the locations of distribution centres for a large food producer with distribution centres throughout the US.

Pooley (1994) and Wouda et al. (2002) both study location-allocation cases from the dairy industry. Pooley (1994) focuses on building a simple model that would be understood and accepted by the management of the dairy company. Wouda et al. (2002) construct a more elaborate model, also including the inter-facility shipment of by-products such as whey and cream, which might be needed in other facilities as ingredients. The resulting model is then used to analyze several production strategies (such as regionalisation of production and distribution, and product specialization at production plants).

	Product	System	Method	Characteristics (with focus on safety, quality and sustainability)
Blackburn and Scudder (2009)	Fresh produce	U|AC	Analytical /scenario analysis	Decreasing product value over time, focus on different transportation options.
Gelders *et al.* (1987)	Beer	RS|U	MILP	Special attention to data collection and estimation of cost parameters
Geoffrion and Graves (1974)	Unspecified	U|U	MILP	General location-allocation model
Groothedde *et al.* (2005)	Palletized	R|U	Heuristic	Study of potential additional hub layer between food manufacturers and retail DCs.
Köksalan and Süral (1999)	Malt	U|U	MILP	Focus on scenario analysis
Levén and Segerstedt (2004)	Wild berries	U|F	Heuristic	Use of load-distance analysis. Frozen storage result of seasonal product.
Pooley (1994)	Dairy	U|U	MILP	Focus on a simple model to aid acceptability by management
Reiner and Trcka (2004)	Pasta	R|U	Simulation	Analysis of different demand situations (in relation to bullwhip effect).
Van der Vorst *et al.* (2009)	Pineapple	R|C	Simulation	Explicit modelling of quality degradation and sustainability issues
Wouda *et al.* (2002)	Dairy	R|U	MILP	Flows of by-products included
Zhang *et al.* (2003)	Unspecified	R|CF	Metaheuristic: Tabu search	Explicit modelling of quality degradation

Table 2.2 Overview of food distribution network design contributions.

The location-allocation problem in the beer industry is studied by Gelders et al. (1987) and Köksalan and Süral (1999). Gelders et al. (1987) analyze the distribution system of a large Belgian brewery, proving that the idea of the brewery to drastically reduce the number of distribution centres is not to be recommended at all. They stress that the increased understanding of the distribution system amongst managers due to extensive what-if analyses is possibly an even more important outcome of their study. In subsequent work, Köksalan and Süral (1999) describe a

follow-up project, which focuses on a different part of the beer supply chain, namely the location-allocation of new malt plants supplying malt to the breweries owned by the same company. The MILP model they develop is extensively used for scenario analysis in cooperation with company personnel.

Zhang et al. (2003) also consider a location-allocation problem, but explicitly include quality degradation of the food product throughout a food supply chain with multiple levels (manufacturers, central warehouses, distribution centres, and retailers/caterers). They include penalty costs for this quality degradation, based on time and temperature throughout the chain. The penalty value depends both on the amount of degradation and the amount of product. In their network design model they introduce a fixed quality degradation parameter for each distribution path from a food manufacturer to a retailer/caterer, and multiply this with the flow quantity to calculate the penalty costs. In addition, they limit the quality degradation permitted during distribution to a maximum. Zhang et al. (2003) then use this penalty cost a tabu search-based solution method.

Levén and Segerstedt (2004) also study a situation in which a location decision needs to be made. The situation described deals with the supply chain of frozen wild berries, a seasonal product that is only supplied during a 4-6-week period, but distributed to customers throughout the year. The authors use a load-distance method to analyze different potential storage locations.

For a large network of food manufacturers and retailers, Groothedde *et al.* (2005) study the possibility to develop a collaborative hub network, aiming to consolidate palletized flows between the production sites of the manufacturers and the distribution centres of the retailers. The main decisions to be made are the locations of the hubs and the determination of fixed transportation paths through the network. For the transport between hubs, shipping on vessels is considered, leading to significant cost savings, but increased transportation times. A combination between the modes of transportation is suggested in which easily forecastable demand is shipped by vessel before the actual order is placed, while the unpredictable part of the demand is delivered on short notice by direct trucking.

Blackburn and Scudder (2009) look at the supply chain of fresh produce that has a deteriorating quality after harvest. The authors minimize product value loss in a hybrid supply chain that initially focuses on responsiveness, to get the product in the cold chain as soon as possible, and once the product is in the cold chain, and value (and quality) deterioration is lower, the focus can be shifted to cost efficiency. The main decision that is modelled in the distribution part of the supply chain is the transportation mode.

Apart from optimization approaches, some authors have also used simulation to study distribution network design. Reiner and Trcka (2004) study a pasta distribution network and investigate how having a distribution centre in the network between production and retail affects the bullwhip effect, looking at different demand patterns (*i.e.*, smooth or volatile). Under volatile demand, the distribution centre does reduce the bullwhip effect, which means a longer distribution chain could be beneficial, opposing the common idea that shorter chains reduce the bullwhip effect.

Finally, Van der Vorst *et al.* (2009) introduce a new simulation environment with the specific aim to support the design and redesign of food supply chains. They stress that the design of distribution networks depends on the desired food quality at the customer, and also call for quality-controlled logistics on the lower decision levels. Next to logistical costs, they include quality decay and sustainability measures. The templates in their modelling environment are developed to include food-specific characteristics, such as quality change for product entities, and climate control for storage and distribution entities. The authors also illustrate the approach for a pineapple supply chain, analysing two possible distribution network designs with regards to costs, product quality, energy use and CO_2 emissions.

2.2.3 Research directions

Despite the importance of the food industry, there is only a limited number of contributions on food distribution network design. Even though all of the discussed papers relate to applications in the food industry, most of them are actually generic facility location-allocation studies; *i.e.*, there are no aspects that make the studies distinctive for the food industry.

The inclusion of product quality was seen in some recent work (Zhang *et al.*, 2003; Blackburn and Scudder, 2009; Van der Vorst *et al.*, 2009), but still seems to be in its infancy. A function like the one introduced by Zhang *et al.* (2003) to calculate the total quality degradation can be used in two ways: as a penalty function in the objective function, or as a constraint where it can be used to limit the total quality degradation in the distribution network. This obviously assumes that it is possible to estimate the degradation between manufacturer and retailer/caterer. A discussion of the impact of operational decisions on e.g. storage duration and transportation and of the microbial and chemical characteristics of the food products is required. Otherwise, extremely conservative values for decay parameters and thresholds need to be used which may impair the efficiency of the distribution operations significantly.

Food safety considerations are thus far not addressed in network design research. Considering the importance of this issue, this provides many opportunities for further work. Distribution network design decisions for instance affect how many actors are involved, how far products travel, and how wide they get spread geographically. These factors have a major effect on food safety and on the sizes of potential product recalls.

Sustainability is explicitly only included in the work by Van der Vorst *et al.* (2009). They relate the travelling distance in networks to the environmental impact. However, considering the relevance of sustainability in the food sector, there is a need for additional work in this direction.

No contribution addresses the specific situation of the foodservice industry. Here, the network design must provide a strong link between production and distribution. Also, the suitable division of production over different stages has not yet been investigated.

2.3 Distribution network planning

2.3.1 Introduction

Distribution network planning concerns mid-term decisions related to fulfilling demand (or forecasts) on an aggregated level. Here, the distribution network is a given, but the focus is on achieving efficiencies in managing distribution as an integrated system (Tayur *et al.*, 1999). The literature on this mid-term decision level covers a large variety of decision problems, and we refer to Mula *et al.* (2010) for a general discussion. In comparison with distribution network design, distribution network planning requires more detailed modelling of production and distribution. Most importantly, a time dimension is added. In optimization models, the time horizon is discretized into periods which are linked through inventory, *i.e.*, food is produced in one period and distributed and consumed in a later period. This may be an efficient way to, for instance, cover a peak in seasonal demand or achieve efficiencies in distribution. This also means that most of the decision-making on distribution is integrated with decision making on production and inventory.

Assessing the range of contributions for our review, it became clear that there are two main research fields studied in relation to food distribution management. First of all, there is a significant amount of work on the planning of aggregate product flows between the various actors in the distribution network which we will discuss in Section 2.3.2. Secondly, a significant amount of work is related to the determination of delivery frequencies. These studies focus on a more detailed level, where the time periods considered are also smaller: mostly days. However, the determined frequencies will be applied for a longer time span. Contributions to this decision problem will be discussed in Section 2.3.3. The remaining contributions on the distribution network planning level will be covered in Section 2.3.4, after which we will conclude with a general discussion of distribution network planning approaches and challenges in Section 2.3.5.

2.3.2 Aggregate flow planning

Modelling approaches in aggregate flow planning often use mixed integer linear programming models similar to the distribution network design models sketched in the previous section. There are however significant changes to incorporate the time dimension and the possibility of keeping product in inventory between periods. A general model for distribution network planning uses continuous decision variables to decide on the product flows in the distribution network for each time period and the inventory levels at the various locations are taken into account. Typical other model constituents include inventory balances and demand coverage constraints. In terms of objectives, there is in the literature again a large focus on financial aspects, occasionally combined with customer-related aspects such as service levels or flexibility (Mula *et al.*, 2010).

Table 2.3 provides an overview of the literature related to aggregate flow planning. These contributions all present models that are similar to the general model outlined above. The main questions that are addressed are related to the production quantities in different plants and the shipment quantities from these plants to retailers, possibly through distribution centres.

A typical approach is found in Duran (1987), who studies the production and distribution network for a brewery. An interesting aspect in relation to modelling food production systems is the distinction the author makes between processing a certain quantity of a food product, and packaging a certain SKU, so that processing and packaging activities are treated separately. This means that next to inventory balance constraints, there are also constraints necessary to balance processing and packaging. Considering that numerous food production systems are structured in these two stages, this distinction is natural and widely applicable.

	Product	System	Method	Characteristics (with focus on safety, quality and sustainability)
Ahumada and Villalobos (2009b)	Packaged fresh produce	U|U	MILP	Selection of transportation mode. Linear quality decay over period of shelf life. Includes crop planning.
Bilgen and Günther (2009)	Fruit juice, soft drinks	R|U	MILP	Demand modelled at DC level. Strong emphasis on production planning. Also including daily vehicle requirements.
Brown *et al.* (2001)	Cereal	R|U	LP	Developed for use on different time scales. Production and packaging treated separately.
Del Castillo and Cochran (1996)	Soft drinks	R|U	LP + Simulation	Inclusion of returnable containers.
Duran (1987)	Beer	U|U	MILP	Large focus on solution approaches like LP relaxations and various decompositions. Production and packaging treated separately.
Ekşioğlu and Jin (2006)	Unspecified,perishable	R|U	MILP	Perishability modelled through maximum number of periods in inventory.
Higgins *et al.* (2006)	Sugar	U|U	MILP + heuristics	Includes assignment of ships to ports (which act as DCs), production costs and capabilities differ for the sugar mills.
Ioannou (2005)	Sugar	R|U	LP	Different packaging types considered. Complete network flexibility in terms of direct deliveries and transhipments.
Rong *et al.* (2011)	Bell peppers	R|C	MILP	Explicit modelling of quality degradation and decision-making on temperature levels

Table 2.3. Overview of food distribution planning contributions – Aggregate flow planning.

Various other special aspects are also considered. In the model presented by Del Castillo and Cochran (1996), a return flow for soft drink bottles is included in the distribution network. Ioannou

(2005) includes a distinction between different packaging formats. Each is treated as a separate flow in the distribution network.

Brown *et al.* (2001) develop a large-scale linear program that models the production and distribution network of the Kellogg Company, a large producer of breakfast cereals and other foods. A noteworthy aspect of the model is that it is developed to function on different time scales, using weeks or, alternatively, months as time units. As in Duran (1987), Brown et al. (2001) distinguish between processing and packaging activities.

For a sugar distribution system, Higgins *et al.* (2006) schedule the shipment of sugar from production sites (mills) to ports that act as distribution centres from which ships are used to export sugar internationally. Overall aims of this study are obviously to improve the efficiency in sugar production and distribution, including port operations, and to support the scheduling procedure, but also to facilitate rescheduling during the season to account for changing production rates which may be due to varying harvesting volumes or qualities. An important aspect of the production of sugar is the setup time required to change to the production of a different type of sugar, which is why Higgins *et al.* (2006) limit the number of product changes over the planning horizon.

Bilgen and Günther (2009) present an integrated model for production and distribution planning. Next to the traditional product flow variables, the distribution part also distinguishes two different transportation modes in the distribution between plants and DCs: full truck load (FTL) and less than truck load (LTL). This *e.g.* leads to the determination of the daily vehicle requirements for FTL shipments and its inclusion in the cost function. As the model also includes production quantities at different locations and related setup settings, total production and distribution costs can be minimized.

The selection of transportation modes is also a main focus of Ahumada and Villalobos (2009b), who study the production and distribution of packaged fresh produce. After packaging the products, the supply chain consists of several more stages in which choices have to be made on using truck, rail or air to transport the products. The authors also include product quality degradation in the model, both in terms of a limited storage time and in terms of a decreasing value of the product over time (based on a linear decrease during the shelf life). Using an index to keep track of the harvest period, the authors are able to track the shelf life. In a typical aggregate flow planning model this leads to the revision of the demand coverage constraint to only include products that have been harvested in the most recent periods (depending on the maximum number of periods the product can be stored).

Regarding the consideration of product quality, a similar contribution is made by Ekşioğlu and Jin (2006), who develop a general MILP approach for network planning of perishable products. Here, perishability is also modelled by a maximum number of periods the product can be stored. In a typical aggregate flow planning model, the authors add a constraint to make sure product inventory in distribution centres is not used to cover the demand after having been stored beyond the specified maximum number of periods. It should be noted that this model assumes that the demands are satisfied from exactly one distribution centre and that the inventories are managed on a first-in-first-out basis.

Finally, a recent contribution by Rong *et al.* (2011) presents a MILP approach for food production and distribution planning, explicitly modelling the quality change of products throughout the distribution network. This is based on the time-temperature profile during storage and transportation of the product, and is also linked to decision-making on the temperatures during storage and distribution. The authors develop a generic modelling approach and apply this in a case study.

2.3.3 Delivery frequency determination

Delivery frequencies refer to a fixed pattern of deliveries to customers. These frequencies were the main topic of several studies. Often, such recurring patterns are fixed for a reasonable time period, as that facilitates retailers/caterers to plan their activities around that. Therefore, the decisions on how often and when exactly customers will get deliveries are made on a tactical level. Table 2.4 gives an overview of the studies focusing on determining delivery frequencies. As opposed to aggregate flow planning, we here also find contributions that exclusively consider distribution-related decisions without including production or inventory aspects.

	Product	System	Method	Characteristics (with focus on safety, quality and sustainability)
Adenso-Díaz *et al.* (1998)	Dairy	R|U	Local search	Hierarchical approach, including *e.g.* the distribution of customers among sales promoters, and the delivery frequency.
Jansen *et al.* (1998; 2001)	Catering products	S|ACF	Simulation	Evaluation of logistic scenarios (delivery frequencies for different product classes).
Pamuk *et al.* (2004)	Beer	R|U	MILP	Modelling the assignment of customers to weekdays, in relation to delivery frequency.
Van der Vorst *et al.*(2000)	Salads	R|C	Simulation	General modelling method for simulating food distribution systems (focus on delivery frequencies).
Zanoni and Zavanella (2007)	Unspecified, perishable	U|U	MILP	Decisions on delivery frequencies and the related number of vehicles used.

Table 2.4. Overview of food distribution planning contributions – Delivery frequency.

To improve the delivery system of a beer producer in Turkey, Pamuk *et al.* (2004) model the assignment of customers to weekdays. The main decision is whether customers get deliveries once or twice a week, and on which day(s), taking into account that the workload of weekdays should be reasonably balanced. Adenso-Díaz *et al.* (1998) also determine on which days of the week a certain customer should be served, but they include several other decisions in a hierarchical approach, such as the distribution of customers among sales promoters to balance their workloads.

In Jansen *et al.* (1998; 2001) and Van der Vorst *et al.* (2000), simulation studies are presented that have wider scope, but in the illustrative scenario analysis the main focus is on delivery frequencies. Van der Vorst *et al.* (2000) additionally considers inventory at the retail level, where out-of-date products have to be discarded. Zanoni and Zavanella (2007) look at a similar situation, but present a generic MILP model to find delivery frequencies and the related number of vehicles for the case of shipping from a single origin to a single destination. Several different product types are included requiring their own vehicle type, which could for instance relate to products that require chilled, frozen, or ambient distribution. The key focus of the model is on cost minimization, while making sure the shelf life of the different product classes is considered in the resulting time between deliveries.

2.3.4 Miscellaneous network planning decisions

Table 2.5 presents the remaining contributions to distribution network planning. These do not fit the two categories presented above: they do not build on the typical flow models presented in Section 2.3.2 nor do they focus on the determination of delivery frequencies as discussed in Section 2.3.3.

	Product	System	Method	Characteristics (with focus on safety, quality and sustainability)
Boronico and Bland (1997)	Turkeys	R|F	Stochastic Dynamic Programming	Seasonal product. Frozen storage at DC. Includes stochasticity in the receipt quantities.
Broekmeulen (1998)	Vegetables and fruits	R|AC	Local search	Product keeping quality is explicitly modelled in development of storage policies for DC.
Dabbene *et al.* (2008a; 2008b)	Fresh food	U|C	Local search	Combination of time-driven and event-driven dynamics. Including a variety of operations conditions relating to physical and timing variables.
Rijgersberg *et al.* (2010)	Fresh-cut iceberg lettuce	R|C	Simulation	Combination of logistical modelling, pathogen growth modelling, and sensory quality modelling.
Rong and Grunow (2010)	Unspecified	U|C	MILP + heuristics	Focus on food safety. Trade-off between dispersion of production batches and production efficiency.
Villegas and Smith (2006)	Cookies, biscuits, crackers	R|U	LP + Simulation	Focus on the relationship between safety stocks and variation in production and distribution quantities.

Table 2.5. Overview of food distribution planning contributions – Miscellaneous.

In relation to order quantities, Boronico and Bland (1997) determine optimal procurement plans for a distribution system of frozen turkeys, which have a distinct seasonal demand pattern, but are supplied throughout the year. The method also includes uncertainty in the actual receipt quantity after ordering.

The management of a distribution centre for vegetables and fruits is studied by Broekmeulen (1998). Here, the minimization of quality loss was the focus of the storage assignment plan developed, basically assigning products to the different temperature zones in the warehouse. Next to temperature, the model includes a variety of other food-related characteristics, such as an interaction between products in terms of their quality degradation. The operational implementation of the assignment plan is studied by use of simulation.

Dabbene *et al.* (2008a) study a distribution network for fresh foods. They present a generic model combining both time-dependent characteristics of food products and distribution aspects. The approach also includes a detailed model of the operational conditions during the processing stage (before distribution). In a companion paper, Dabbene *et al.* (2008b) consider a case study of a fresh-food supply chain in which they study the decision-making on refrigeration power used and processing time before distribution. The product temperature can be adjusted in combination with distribution decisions, with the objective to deliver the product at a certain time and a certain temperature.

Rijgersberg *et al.* (2010) develop a simulation model of the distribution chain of fresh-cut iceberg lettuce. The focus of this model is on the quality and safety of the product being distributed. The authors analyse various scenarios, investigating primarily food safety aspects, by studying the growth of *Listeria Monocytogenes*, a relevant pathogen in this type of food product. Next to this, product shrinkage and retail out-of-stock are considered as additional performance measures. The main focus is on the impact of use-by-dates, customer selection behaviour in stores (steering the customer towards buying the older products), and lead time reduction in the distribution chain.

Production batches get dispersed when distributed through in a distribution network. Rong and Grunow (2010) investigate the implications for food safety management. Their idea is that decreasing dispersion by using smaller production batches would be beneficial in case of food safety problems, but on the other hand decreases production efficiency. Their approach is able to support this trade-off based on the risk attitude of the decision maker.

Villegas and Smith (2006) study the relationship between inventories and variations in production and distribution order quantities. They develop a System Dynamics model to show the dynamics of the distribution network, and the occurrence of the bullwhip effect. They also provide LP models that are used to mimic the behaviour of an Advanced Planning System. Using these models, the authors show that most of the demand variation leads to adjustments in production and distribution quantities, while capacity shortages lead to the use of additional inventories. Finally, they provide an alternative planning model to reduce the variability in production and distribution quantities.

2.3.5 Research directions for distribution network planning

Based on the contributions discussed, it is clear that there is a wide variety of decisions being supported by the modelling work on the network planning level. Various approaches based on aggregate flow planning were discussed, mostly on fairly coarse time discretization. On a more detailed level, several studies focused on the aspect of delivery frequencies. Finally, work was discussed that did not fit in the categories for aggregate flow planning or delivery frequency determination. This last category showed some interesting examples of how food quality and safety can be addressed on this decision level.

Regarding food quality, there are some studies that explicitly model continuous quality change, and some others that deal with the issue implicitly. Implicit modelling approaches toward quality change can be found in Brown et *al.* (2001) and Ekşioğlu and Jin (2006), who consider a limitation on product storage time so as to avoid product spoilage. Broekmeulen (1998) models quality degradation during storage explicitly and investigates different storage policies for vegetables and fruits, using a penalty for quality changes above a certain maximum. However, Broekmeulen (1998) only focuses on minimizing quality change and does not look at the trade-off between quality loss and storage, handling or transportation costs. Rong *et al.* (2011) however integrate decision-making on logistical issues with issues affecting food quality degradation, such as initial quality levels and temperatures during storage and transportation. They use a discretized quality scale to track product quality throughout the production and distribution system. It should be noted that modelling approaches with time discretization in months (as is typical in aggregate flow models) are only applicable if the quality decay of the food is limited. If highly perishable food is regarded, the time discretization (and the problem horizon) needs to be adjusted, which leads to problems in terms of computational tractability, or suitable aggregation schemes need to be developed. The development of suitable mathematical modelling approaches hence still needs further research. In an alternative approach, Jansen *et al.* (1998; 2001) and Van der Vorst *et al.* (2000) therefore used simulation modelling to handle product quality as a performance indicator next to cost aspects.

Food safety has also seen only limited (and recent) consideration in the reviewed work. Rong and Grunow (2010) aim at reducing the impact of possible recalls by reducing the dispersion of production batches in distribution networks. The work presented by Rijgersberg *et al.* (2010) provides a promising simulation approach combining microbial risk assessment with logistical modelling.

It is noteworthy that sustainability does not seem to have gotten any attention on the distribution network planning level. Some of the studies do however contain cost elements that also have an environmental side, such as the temperature control factors included by Dabbene *et al.* (2008a; 2008b) and Rong *et al.* (2010). These factors relate to energy use for refrigeration, an important aspect in the discussions around the environmental impact of food transportation.

Finally, it is worth noticing that, so far, the focus of the literature has been mainly on retail chains, leaving the distribution challenges in foodservice behind. Only Jansen *et al.* (1998; 2001) focus on this industry

2.4 Transportation planning

2.4.1 Introduction

Transportation planning concerns the short term planning of the distribution operations and mostly deals with the planning of deliveries to different customers. Transportation plays a key role in today's economies; accounting for up to two-thirds of the total logistics cost. Moreover, it also has a major impact on the level of customer service (Ghiani *et al.*, 2004). Transportation planning takes place in a highly dynamic environment requiring frequent re-considerations of previously made decisions (Crainic and Laporte, 1997).

Typical decisions on this decision level are the details of delivery routes; at what exact times, by which vehicle, and in what sequence customers will get their products delivered. In addition, also warehousing decisions may have to be made on the operational level, such as the assignment of inbound and outbound trucks to dock doors. For a more comprehensive discussion of decisions related to operational warehouse operations, we refer to Gu *et al.* (2007).

For certain food products, international agreements have been made to regulate the transportation of chilled and frozen foods. In a recent paper, Panozzo and Cortella (2008) argue for the extension of these agreements to other perishable food products, such as prepared dishes, and (minimally processed) fruits and vegetables. Next to increased food safety and quality, Panozzo and Cortella (2008) expect that this would also lead to positive economic and environmental effects, mainly resulting from decreased energy consumption.

As outlined in the introduction chapter, the transportation of food products requires different temperature levels. A vehicle may be divided up into multiple compartments with different temperature control. A recent paper by Derigs *et al.* (2010) provides a general model for multi-compartment vehicles, also stressing that most of the previous work in this area concerns fuel distribution and is hence not relevant for this review.

Most approaches in the transportation planning part of our review are based on the well-known vehicle routing problem (VRP), often including delivery time windows. A basic mathematical programming formulation of such a problem would use binary decision variables to denote whether a trip from a location to another location is included in the route for a specific vehicle. For each of these locations the model includes delivery time windows: an earliest delivery time and a latest delivery time. Objectives are often the minimization of total duration of the routes, the minimization of the total distance travelled, or the minimization of the total number of vehicles needed to perform the deliveries (Bräysy and Gendrau, 2005a). Our paper only focuses on food transportation problems and their characteristics. For a detailed discussion of general vehicle routing problems we refer to early work by Dantzig and Ramser (1959) and Golden *et al.* (1977), the seminal paper by Bodin *et al.* (1983) or the more recent review on vehicle routing problems with time windows by Bräysy and Gendrau (2005a).

Mathematical programming models often become large and hence computationally time-consuming. For this reason, heuristic approaches are normally developed to be able to solve the

routing problem within reasonable time. For a detailed discussion of solution methods, we refer to Bräysy and Gendrau (2005b) or Tarantilis *et al.* (2005).

2.4.2. Contributions

Table 2.6 presents an overview of the literature on food transportation planning. As mentioned in the previous section, the work on this planning level mainly encompasses contributions related to VRP applications to the food industry. For this reason, we also chose to present two columns with model characteristics. The first contains characteristics that distinguish the contribution from a VRP perspective, whereas the second contains (food-specific) additional characteristics. In the first column, we only presented characteristics that make the contribution different from a standard VRP problem. Here, we understand the standard VRP problem to consist of one distribution centre (or depot) from which certain quantities of a single product have to be delivered to several customer locations (no split delivery), using an undetermined number of identical vehicles. These vehicles have to return to the distribution centre, and only do one delivery tour each.

Most contributions use a heuristic approach to solve the routing problems; well-known construction and improvement methods are used. Therefore, Table 2.6 does not include information on the solution methods. The only paper that does not use such a heuristic approach is De Angelis *et al.* (2007), who employ integer programming. It should however be noted that the problem these authors study is fairly small, and also contains some simplifying assumptions, for example are only full cargo loads distributed to customers.

	Product	System	VRP characteristics	Special characteristics
Adenso-Díaz *et al.* (1998)	Dairy	R|U	Heterogeneous vehicle fleet, time windows	Whenever possible, additional customers in the same town that are initially scheduled for a separate visit are added to a route.
Ambrosino and Sciomachen (2007)	Highway food store supplies	R|CF	Multi-product, split delivery	Use of compartmentalized trucks to distribute different products, maximum number of stops for frozen products.
Bartholdi et al. (1983)	Meals	S|A		Creation of a very simple heuristic, no computer support required.
Belenguer *et al.* (2005)	Meat	RS|U	Heterogeneous vehicle fleet, time windows	Preferred zones to take advantage of drivers' knowledge.
Carter et al. (1996)	Groceries	R|U	Time windows	Combined approach with decision on delivery quantities, based on delivery costs, inventory costs, and backorder costs
Chen and Vairaktarakis (2005)	Unspecified	S|U	Multi-product	Combined with production scheduling, also to study the value of this integration.
Chen *et al.* (2009)	Unspecified, perishable	R|U	Multi-product, time windows, stochastic demands	Combined with production scheduling, product value continuously decays after production.
Cheong *et al.* (2002)	Soft drinks	U|U	Heterogeneous vehicle fleet, multiple trips, split delivery	Grouping of customers in zones, and detailed routing within those zones. Daily planning allows vehicles to help other zones.
Chung and Norback (1991)	Food-service products, also perishables	S|ACF	Heterogeneous vehicle fleet, time windows	Combined with allocation of drivers and vehicles, also related to refrigeration requirements. Extension to earlier work by Evans and Norback (1984, 1985)
De Angelis *et al.* (2007)	Food aid	U*|U	Multi-depot, multiple trips, fixed fleet size	Model maximizes total demand satisfied by IP, using only full cargoes. (* Chain structure unspecified because food aid does not fit into the traditional retailer – foodservice distinction)

Faulin (2003a, 2003b)	Vegetables	R|F		Truck utilization restricted by product specifics (safety of transporting canned goods).
Hsu *et al.* (2007)	Unspecified, perishable	R|CF	Time windows, time-dependent travel times	Explicitly models the perishability of food using a decreasing value over time. Dependent on both tour length and number of times the cargo hold is opened.
Hu *et al.* (2009)	Meat	R|C	Heterogeneous vehicle fleet, open routes	Special attention to network structure in metropolitan area.
Osvald and Stirn (2008)	Vegetables	R|U	Time-dependent travel times, time windows	Including a linear product quality loss over time.
Privé *et al.* (2006)	Soft drinks	U|U	Multi-product, heterogeneous vehicle fleet, time windows, pickup and delivery	Including the collection of recyclable containers
Rochat and Semet (1994)	Flour and pet food	R|U	Heterogeneous vehicle fleet, time windows	Inclusion of driver breaks, customer vehicle type constraints
Semet and Taillard (1993)	Groceries	R|U	Heterogeneous vehicle fleet, time windows	Trucks can have trailers, which can be dropped off for subtours (affecting customer vehicle type constraints, as well as costs)
Tarantilis and Kiranoudis (2001)	Dairy	R|U	Heterogeneous vehicle fleet, fixed fleet size	
Tarantilis and Kiranoudis (2002)	Meat	R|U	Multi-depot, open routes	Development of a general meta-heuristic, based on threshold accepting algorithms
Van Vliet *et al.* (1992)	Sugar	U**|U	Heterogeneous vehicle fleet, fixed fleet size, multi-depot, time windows	Combined with bulk truck loading (** Business-to-business delivery)
Zeng *et al.* (2008)	Soft drinks	U|U	Heterogeneous vehicle fleet, multiple trips, split delivery	Alternative methods to solve problem described by Cheong et al. (2002), significantly reducing the number of vehicles required.

Table 2.6. Overview of food transportation planning contributions.

Looking at the characteristics of the VRP problems studied, we see that most authors extended the basic VRP problem. Most common is the inclusion of time windows. In some cases this is just included to make sure the retail stores that have to be supplied are open (Rochat and Semet, 1994), but in most cases the time windows are shorter, and often they are similar. For instance, in the meat distribution example presented by Belenguer *et al.* (2005), most butchers would like to be supplied early in the morning. Secondly, a distinction between different types of vehicles is made. This characteristic is often included to distinguish between different vehicle capacities (*e.g.*, Belenguer *et al.*, 2005; Tarantilis and Kiranoudis, 2001) or the potential use of a trailer (Semet and Taillard, 1993). However, in the situation described by Chung and Norback (1991) the distinction also includes different refrigeration capabilities, which is essential to consider in food distribution. Finally, some recent contributions (Hsu *et al.*, 2007, Osvald and Stirn, 2008) also include time-dependent travel times, which are becoming more and more relevant on today's busy road networks. The difference in travel times between rush hours and non-rush hours can be significant, and often needs to be taken into account.

We can also see in Table 2.6 that a wide variety of food products has been studied, ranging from single-product distribution such as sugar (Van Vliet *et al.*, 1992) to distribution of different products to retail outlets (Ambrosino and Sciomachen, 2007; Carter *et al.*, 1996) or caterers (Chung and Norback, 1991). Some recent contributions (Hsu *et al.*, 2007; Chen *et al.*, 2009) develop general approaches for perishable food products, making their models generally applicable for most food products.

Table 2.6 also presents an overview of the special characteristics covered in each of the studies. For instance, one of the earliest contributions (Bartholdi *et al.*, 1983) focuses on creating a heuristic that would be usable without the use of a computer. Even though the presence of computers is not a big issue in the current time, it is still interesting to see that a simple clustering approach is able to lead to a reasonable performance, and might still be useful for the many SMEs that operate in the food industry. More recent work by Belenguer *et al.* (2005) and Cheong *et al.* (2002) are also based on clustering customers into zones, but these authors do this to be able to take advantage of the drivers' knowledge of the specific regions.

In order to explicitly model product quality, Chen et al. (2009) present an approach that includes a decrease in product value over time, and incorporate that in a model aiming at profit maximization. Osvald and Stirn (2008) quantitatively control the quality of products by considering a linear relationship between quality and transportation time. Most contributions do not specifically mention the temperature during distribution. However, a few papers specifically mention or consider chilled or frozen distribution (Ambrosino and Sciomachen, 2007; Chung and Norback, 1991; Hsu *et al.*, 2007; Hu *et al.*, 2009). An interesting factor considered in some of these contributions the stops of the vehicles, relating to how often the temperature-controlled cargo hold has to be opened (Ambrosino and Sciomachen, 2007; Hsu *et al.*, 2007). The reasoning behind this is that these temperature disruptions negatively affect the food product. Ambrosino and Sciomachen (2007) limit the quality degradation of products during transportation by setting a maximum number for the number of stops for each vehicle carrying frozen products. Hsu *et al.* (2007) assume that the degradation in quality happens mainly during the time that the cargo hold is open and

vehicles are serving the customers. For an otherwise typical VRP model, this leads to an additional term in the objective function related to the total expected loss of food product. This expected loss is calculated dynamically dependent on the time elapsed since vehicle departed from the distribution centre and the time the cargo hold is opened (which in turn depends on the customer demand volumes at the individual customer sites visited thus far). Another interesting characteristic, included by Ambrosino and Sciomachen (2007), is the use of compartmentalized trucks to distribute different products at different temperatures.

Finally, one contribution does not present a variety of a VRP problem, and is therefore not included in Table 2.6. Boysen (2010) deals with the operational scheduling of trucks at a cross-docking terminal. The author considers frozen foods and assumes that there is no possibility to store products as that would lead to defrosting and product degradation. This means that the inbound and outbound operations are strongly connected and should be synchronized. To do this, Boysen presents dynamic programming and heuristic procedures that are able to solve real-life-sized problems.

2.4.3 Research directions

Keeping quality during transportation of foods is a challenge for food distributors. This issue has mostly been considered implicitly by assuming that the planning horizon is shorter than the shelf life of the products or by minimizing transportation time and distance. Among the available literature, only selected studies take a more explicit approach toward modelling food quality during transportation. However, it should be noted that these papers manly model quality degradation as a (continuous) decrease in product value (often starting from the start of distribution), which might not be the kind of quality decay that is experienced with all food products. Often, a product would be considered completely perished at a certain quality level. Because initial quality status might not be easily detectable, it can be hard to estimate the remaining shelf life in such cases. Modelling degradation throughout the network in a proper way would be of significant benefit. Related to this is an effort to improve coordination between production and transportation planning, allowing for better quality control. This is an area that deserves further research, especially for products that are highly perishable. The importance of coordinating production and transportation has also recently been stressed by Chen (2010), who presented the state of the art on modelling integrated production and outbound distribution scheduling.

One approach (Faulin, 2003a, 2003b) explicitly mentions safety in transportation of canned food products. However, Faulin's approach towards safety is only related to physical safety of transportation operations, and not the safety of food products. Therefore, there is still a significant opportunity for operations management researchers to identify efficient ways to improve safety measures and to reduce the impacts of safety problems. Several approaches try to utilize driver knowledge by assigning certain groups of customers to the same driver. Indirectly, this is a way to increase food safety, as the driver's knowledge would also include information of food control systems used by the customer (including *e.g.* temperature checks and sampling for quality control). Also, the development of methods that use or improve the traceability of foods in the chain has not

been considered so far, and could be one way to improve the safety of foods. This could be based on some recent approaches that look at the dispersion of raw material or production batches in production and distribution systems (Dupuy *et al.*, 2005; Wang *et al.*, 2009b; 2010; Rong and Grunow, 2010). So far, this concept has not been used in relation to transportation planning, but it seems logical to also use this in these decision problems. As such approaches rely on extensive product information; they should be supported by tracking and tracing models, such as the one that has recently been developed by Fritz and Schiefer (2009).

Hsu *et al.* (2007) take the sustainability of the transportation system explicitly into account by trying to reduce the energy consumption. The reverse product flow included by Privé *et al.* (2006) is also a relevant contribution to the sustainability of distribution systems, as the environmental impact of distribution does not stop after a product is delivered; a reverse flow is often found, ranging from empty containers or boxes in the retail industry to bowls and plates in the foodservice industry. Including these flows in modelling approaches can be very useful to in relation to sustainability, and could for instance be used to evaluate the impact of using recyclable packaging material. Developing these models would improve the possibilities for a proactive approach to sustainability; deciding on when and where to use certain transport or package options to minimize the environmental impact of distribution, something which is currently lacking in the quantitative operations management literature.

2.5 Integrated approaches

So far, this paper dealt with distribution management challenges on the strategic, tactical and operational level. In some cases however, it makes sense to integrate the decision making on different hierarchical levels. For example, in a recent survey of supply chain network design studies, Melo *et al.* (2009) show that about 60% of the papers in their review extends beyond the basic location-allocation problem. This section will outline the most important applications of such integrated approaches found in relation to food distribution management. Table 2.7 provides an overview of these contributions, also identifying what decision levels are involved in the integration.

	Product	System	Method	Decision level			Characteristics (with focus on safety, quality and sustainability)
				S	T	O	
Custódio and Oliveira (2006)	Unspecified	R|F	Heuristic		X	X	Focus on the trade-off between inventory cost and transportation cost. Includes estimation of safety stock levels.
Federgruen et al. (1986)	Unspecified, Perishable	U|U	Heuristic		X	X	Inclusion of different product classes for fresh and old products. Out-of-date cost in objective.
Hwang (1999)	Food aid	U*|U	Heuristic		X	X	Food supply to famine relief areas. Assignment of limited supplies to needy locations and clustering of 'customers' and routing of vehicles in a hierarchical way. (* Chain structure unspecified because food aid does not fit into the traditional retailer – foodservice distinction)
Köksalan *et al.* (1995)	Beer	U|U	MILP	X	X		Focus on location of breweries. Inclusion of seasonal demands, requiring the inclusion of more detailed production decisions.
Rusdiansyah and Tsao (2005)	Vending machine supplies	U|U	MILP + heuristics		X	X	Focus on the trade-off between inventory cost and transportation cost. Deciding delivery frequency in combination with vehicle tours.
Watson-Gandy and Dohrn (1973)	Unspecified	R|U	Scenario analysis	X		X	Selection of warehouse locations, with sales amounts that are decreasing with distance.

Table 2.7. Overview of integrated approaches to food distribution management.

Decision levels: strategic distribution network design (S), tactical distribution network planning (T), and operational transportation planning (O).

2.5.1 Combining network design with network planning

Typically, distribution network design modelling does not consider a time aspect, but only focuses on *e.g.* yearly average flows. This mostly leads to MILP models without time indices (as discussed in Section 2.2). Distribution network planning, on the other hand, deals with more detailed

decision-making, where the time dimension is more prominent in the modelling efforts (see Section 2.3).

Köksalan *et al.* (1995) study a distribution network design problem, in which they focus on the location of the breweries, but they model production on a more detailed level, to be able to include the effects of seasonal demands in relation to production capacity utilization and inventory build-up towards the summer months. This leads to a model that combines elements from the distribution network design and distribution network planning models discussed in the previous sections. The trade-off between investing in excess capacity or investing in inventory is essential in their decision problem. To do this, Köksalan *et al.* (1995) add more detail to their model to track monthly production and inventory. Using this, the cost of building up inventory in the off-season can be added to the objective function.

2.5.2 Combining location decisions with transportation planning

A typical combination of decisions on the strategic and operational level is the facility location decision and the subsequent vehicle routing. The reasoning behind this is that the total cost of the distribution system can be minimized by taking the short-term routing decisions into account in facility location problems. This would lead to solutions that are able to take advantage of an efficient non-fragmented distribution of goods, which might result from separate decision-making (Min *et al.*, 1998). As such, location-routing is location planning with tour planning aspects taken into account (Nagy and Salhi, 2007). These approaches do however assume that it is possible to determine realistic routing plans on a long time horizon, which might be difficult considering the often dynamic behaviour of customers. Routes change significantly when minor changes in demand volumes or shifts in time windows occur, which are likely to happen within the time horizon considered in location decisions.

One of the first contributions in location-routing for food products deals with a British food and drink company, which is reconsidering its warehouse locations (Watson-Gandy and Dohrn, 1973). In the distribution costs, the authors consider (*i*) costs for local delivery from warehouses to customers, based on average tour distances for a certain number of customers visited, (*ii*) costs for shipments between plants and warehouses and (*iii*) costs for the depots. The approach aims at maximizing profits, while account for sales which decrease with the customer distance from the warehouse.

Although there are numerous studies dealing with location-routing problems in the literature, specific applications to food distribution systems seem to be limited to the article by Watson-Gandy and Dohrn (1973). For more details on the existing general location-routing literature, we refer to Nagy and Salhi (2007).

2.5.3 Combining inventory decisions with transportation planning

It can sometimes be difficult to consider the operational problem of transportation planning, without affecting more tactical issues like inventory decisions. Integrated inventory-routing approaches try

to minimize short-term vehicle routing cost or distances, while also looking at the longer-term cost factors related to inventory levels and delivery frequencies (see *e.g.* Federgruen and Zipkin, 1984; Moin and Salhi, 2007).

The general model presented by Federgruen and Zipkin (1984) is generalized in Federgruen *et al.* (1986) for perishable products. More specifically, they identify separate product classes for fresh and old product, using a fixed lifetime for the product. This also leads to an out-of-date cost in their objective function, reflecting the cost of discarding product.

Some more recent work has been done by Rusdiansyah and Tsao (2005) and Custódio and Oliveira (2006). Both of these papers focus on the trade-off between inventory and transportation cost. For a frozen food distribution network, Custódio and Oliveira (2006) study the integration of inventory management and vehicle routing, and devise a heuristic procedure to solve this problem where demand is considered to be deterministic at this stage. The model helps to determine the inventory levels, safety stocks, inventory replenishment frequencies for the products, and the vehicle routes. Rusdiansyah and Tsao (2005) look at a distribution network for the supply to food vending machines, deciding on delivery frequency in combination with vehicle tours. Both of these studies do however not include any food-specific characteristics.

Another application of inventory-routing of food products is presented by Hwang (1999), who studies a distribution network in a famine relief area. Although the paper does not provide much detail on the modelling work, the authors suggest a hierarchical approach which first assigns inventory to the various locations in need of food. Then, in subsequent steps, these locations are assigned to supply centres and vehicle routes are created, both based on heuristic methods.

For more details on inventory-routing studies, we refer to recent overviews presented by Moin and Salhi (2007) and Andersson *et al.* (2010).

2.5.4 Research directions

The contributions described in this section crossed the traditional boundaries of the hierarchical framework presented in Section 2.1. The main reason for this seems to be the need to include more detailed analysis, leading to an extension of the models into lower decision levels. There has only been limited attention to food quality in these contributions and none to food safety and sustainability. The modelling work by Federgruen *et al.* (1986) includes a cost aspect for perished products. The inclusion of some tactical decisions in a strategic decision problem studied by Köksalan *et al.* (1995) is done to be able to include the effects of seasonal demands. Considering that numerous food products experience seasonality – in demand or supply – this approach seems a valuable extension of the standard models for location decisions in this industry.

2.6 Conclusion and discussion

In this paper, we have reviewed the quantitative operations management research on food distribution management. Our contribution lies in the classification of the literature in a hierarchical

framework consisting of distribution network design, distribution network planning, and transportation planning. Furthermore, within each of these levels, we survey the research contributions, discuss the state of the art and identify challenges for further research. Special focus is given to the aspects of food quality, food safety and sustainability.

2.6.1 Main conclusions

In general, it has to be noted that most of the literature on food distribution management does not cover the key challenges found in the food industry. Most noticeable in the review is that there are very few studies in the literature that include food safety aspects in distribution management.

The importance of product quality is, however, reflected to a slightly larger extent in the current research, both in the number of contributions and in the variety of the methodology used. A number of papers include quality changes implicitly by limiting product storage or transportation time, other papers model quality decay explicitly be including a cost factor or degradation parameter dependent on the path chosen or the time required.

In general, these approaches are based on only a very rough approximation of quality degradation, which hence leads to extremely conservative quality decay parameters and thresholds to make sure that the quality is sufficient for all products independent of the often varying initial quality status, the chemical and microbial properties of the food, the environmental conditions and distribution operations. Furthermore, such an approach often results in local operating rules such as the definition of a maximum storage time in a DC, and hence does not permit trading off additional storage time in a certain stage in the distribution network with *e.g.* a faster delivery elsewhere in the network, or with other means of keeping quality degradation within limits.

Most of the contributions reviewed in this paper do not specify the temperature level during distribution, even though temperature control is a main factor with regards to the control of food quality and food safety. The exceptional work that does specify the level of temperature control mostly does not integrate any related quality or safety aspects in the presented modelling approaches. A notable exception is the work on the transportation planning level taking into account the opening of the cargo hold; acknowledging the effects this would have on the temperature the food products are exposed to (Ambrosino and Sciomachen, 2007; Hsu *et al.*, 2007). Rong *et al.* (2011) explicitly track quality through a production and distribution network and integrate logistical decision-making with temperature control, and Van der Vorst *et al.* (2009) integrate quality changes depending on time and temperature in their simulation approach..

Even though today's society is more and more concerned with sustainability, this review shows that there is only very limited attention to designing and operating sustainable food distribution networks. In the few cases in which sustainability is considered, it mainly concerns the environmental dimension of sustainability. The lack of attention to the social dimension is likely due to the fact that it is harder to quantify.

Finally, it is worth mentioning that most of the research so far is aimed at the retail industry, whereas the foodservice industry received much less attention. This is probably highly related to the

prevalence of SMEs in this sector, where the development and use of the kind of decision support models described in this paper is less common than in the larger companies found in the retail industry. However, it should be noted that recent developments in the retail sector, such as the increasing use of EPoS data in ECR initiatives is not reflected in the literature.

2.6.2 Future research directions

Developing planning approaches for distribution network structures and operations that can contribute to an increased product safety is something that requires more attention. Although legal frameworks have been put in place to improve safety of final food products, leading to the development of safety management systems like HACCP, supporting the development of these systems in a quantitative way has hardly received any attention. For instance, the positioning of critical control points in a distribution network is an important aspect that might be worth additional attention by researchers. A possible starting point would be the methodology Bertolini *et al.* (2007) propose for the determination of critical control points in food manufacturing systems. In the brainstorming processes normally used in practice, decision making is typically hindered by an inability to discriminate and prioritize risks. The structured method by Bertolini *et al.* might be a way to include these aspects in quantitative operations management approaches, allowing for managers to gain more insight in trade-offs between *e.g.* food safety and related costs. Also, designing distribution networks that can react appropriately when a safety crisis occurs is a key research challenge. For instance, as product recalls can be a major challenge and a significant expense, designing and operating a distribution network that facilitates the rapid identification of affected products and that limits the size of product recalls can reduce the exposure of final consumers to food safety crises and increase the reliability and ultimately subsistence of food distribution systems.

Quality changes during distribution were considered by some authors. In most cases, however, the integration of product quality still requires significant simplification of the dynamic process of quality change. Considering the increasing focus on high-quality food products, in combination with the globalized food market, this remains a challenging research area. Here, we also want to reiterate the point made by Apaiah *et al.* (2005) that designing food distribution systems that are able to provide high-quality food in a cost-efficient way is a challenge that requires an interdisciplinary focus with efforts from *e.g.* food engineering and operations management. It is also important to note that there is a lack of approaches that are able to cope with multiple products having different shelf lives and supply and demand patterns, which is a finding that has also been reported in relation to analytical approaches to the inventory management of perishable products (Prastacos, 1984; Karaesmen *et al.*, 2011).

Regarding the temperature control during distribution, the recent developments in tracking temperature during distribution using time-temperature indicators, provides opportunities for further research. The additional knowledge gained from these technologies would allow for more advanced decision making with regards to *e.g.* the modelling of quality degradation or the impact of cargo hold openings during transportation.

Defining new methods to quantify and integrate performance indicators from the different sustainability dimensions also remains a challenge for future research. This involves a broad perspective on triple-bottom-line thinking, integrating profit, people, and the planet into the culture, strategy, and operations of companies (Kleindorfer *et al.*, 2005). Including aspects such as CO_2 emissions or product waste in the design and management of food distribution systems is a necessary step in this research area. Recent developments in relation to social life cycle assessments might provide the possibility to quantify some of the social aspects, which would facilitate the inclusion of this dimension in quantitative operations management research, and would significantly improve the capabilities of companies for managing (and reporting) their Corporate Social Responsibility activities. Further, an integration of different sustainability indicators would give significant insight in the trade-offs between economic, environmental, and social performance indicators and also lead to an improved knowledge base for discussions between the private and public sector on the governance of food distribution, for example on the issue of local versus global sourcing.

In sum, quantitative operations management research still has a long way to go until a comprehensive methodology is in place on which managers can draw when seeking decision support in food distribution which is able to cope with the key challenges the industry is currently facing in managing quality, safety and sustainability.

We structured our analysis according to the traditional hierarchy of the decision problems. However, it has also been shown that the implementation of hierarchical planning structures and algorithms can be difficult in practice and modelling the relationship between hierarchical levels is one of the main difficulties in implementing decision support tools such as Advanced Planning Systems (Zoryk-Schalla *et al.*, 2004). One of the main challenges that has to be overcome is inherent in hierarchical planning approaches: the issue of aggregation-disaggregation, mainly referring to the coordination of different levels of detail in modelling (Schneeweiss, 2003). At the higher level, anticipation mechanisms must be developed, which represent the lower level decision problem in an aggregate way. In food distribution management, this mainly seems to be related to the inclusion of food quality and safety. Both of these aspects are normally modelled on detailed time scales, to be able to include the dynamics of microbial and chemical processes. How to anticipate for that in models on strategic and tactical levels, where time scales are normally coarser is an open question. This so-called temporal aggregation requires the development of suitable aggregation mechanisms and will be a central problem in future research.

Especially when dealing with product safety, it is often necessary to include stochastic risk information in the modelling approaches. Here, the simulation approach presented by Rijgersberg *et al.* (2010) seems very suitable to study the impact of distribution network decisions in light of microbial risk assessment. However, when the number of alternative solutions is large, the integration of this stochastic risk information in optimization approaches is required. Combining mathematical programming with simulation might be one way to achieve this in future research.

In light of the growing importance and increasing industrialization seen in the foodservice sector, the current lack of attention to this industry will become even more significant. This industry

mostly deals with fresh food. Hence, production and distribution are closely connected. This leads to challenging research issues in relation to an integrative treatment of these stages. Such work can also profit from data-driven initiatives like ECR and EFR.

In addition to sales data, vast amounts of distribution information become available due to the recent traceability efforts of the food industry. Utilizing this information not only to adhere to the legal requirements but also to improve the efficiency, quality, safety and sustainability of food distribution systems is the logical next step. The advantages of utilizing this traceability information extend from the quality and safety benefits that originally led to the introduction of traceability to the minimization of recall sizes and the improvement of operational efficiency along the supply chain (*e.g.*, Wang et al., 2009a). Quantitative operations management research has the ability to advance these potential benefits from the conceptual stage to specific decision support for food producers and distributors.

Chapter 3. Integration of production and distribution operations

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Abstract

Certain types of food, such as catering foods, decay very rapidly. This paper investigates how the quality of such foods can be improved by shortening the time interval between production and delivery. To this end, we develop an approach that integrates short-term production and distribution planning in an iterative scheme. Further, an aggregation scheme is developed as the interface between the production scheduling and distribution problem. The production scheduling problem is solved through an MILP modeling approach which is based on a block planning formulation. Our implementation shows promising results, elaborated in a numerical investigation, which recollects the real settings of a catering company located in Denmark.

3.1 Introduction

A commodity is called perishable if its quality or quantity is subject to deterioration. A group of perishable products comprises goods in which product quality is subject to a continuous change after the production stage. Fresh foods, bakery products and blood products are some well-known examples of this category. Fresh foods create unique supply chain challenges. Foods such as fruits, vegetables, and meat need to be nurtured to ensure that they remain in good quality. This includes monitoring the time that this delicate cargo spends in stock and during transport in the supply chain - the most critical time for all fresh foods. It is essential to deliver such products right after production to limit quality degradation. Therefore, a tight coordination between the production and distribution systems is necessary which can be realized by integrating the planning of these two stages of the supply chain.

Motivated by a case study from a food caterer in Copenhagen, we develop mathematical models and a heuristic solution method to investigate the effect of integrating production scheduling and distribution decisions on the total costs and the quality of the delivered products. The distribution problem involves designing vehicle routes and schedules for picking up prepared foods and delivering them to customers. On the production site, food production orders must be scheduled on available production lines. Moreover, the setup cost for producing each food type strongly depends on the product type produced in the previous production run, i.e. the setup costs are sequence-dependent.

In such a supply chain, product quality is determined not only by the production processes, but also through the coordination of the production and distribution decisions. To ease this coordination, food preparation sites are usually directly connected to customers by a fleet of vehicles operated by the caterer. However, the analysis of practices at the Copenhagen-based caterer shows that currently the production and distribution stages are handled independently, causing large operational and quality problems. In this paper, we therefore investigate how an integrated planning approach can be used to harmonize production and distribution decisions aiming at a trade-off between the quality of delivered products and the total costs.

The contribution of our study is in integrating fresh food production and distribution planning. An iterative solution framework is developed to investigate the effect of such integration on total costs as well as on the quality of delivered products. We reduce the problem complexity through developing a hierarchical modeling approach, which splits the overall planning problem into a production and a distribution sub-problem. In addition, an aggregation procedure is applied to group customer orders into production batches. A practical approach called block planning is employed for developing the mixed-integer linear programming (MILP) formulation of the production scheduling problem. The distribution problem is solved through a Large Neighbourhood Search algorithm (LNS). Experimental scenarios, designed for critical aspects of the planning problem, reveal the impact of the integrative approach on the overall solution quality.

The remainder of this paper is organized as follows. In the next section, a brief review of the relevant literature on production scheduling and distribution planning in fresh food industries is presented. In Section 3.3, the practical planning problem is presented in detail and the motivating catering case study is explained. In Section 3.4, our hierarchical modeling approach consisting of a heuristic order batching procedure, the production scheduling model which is based on the block planning principle, and the distribution planning heuristic is introduced. In addition, the iterative solution procedure is presented. The results of our numerical studies are presented in Section 3.5. Finally, conclusions are drawn and further research directions are discussed in the last section.

3.2 Literature review

The production scheduling problem in fresh food industries, as briefly discussed in Section 1, represents a famous class of problems referred to as scheduling with sequence-dependent setups that are well known to be NP-hard (Sun et al., 1999). A complete survey of production scheduling problems with setup consideration is presented in Zhu and Wilhelm (2006) and in Allahverdi et al. (2008). A common difficulty in these problems is the complexity of the resulting models. To overcome such difficulty, Günther and Neuhaus (2004) developed an approach, named block planning. Applications of the block planning concept have not been widely investigated in literature, although this policy is easy to implement and provides decision makers with managerial insights. Günther and Neuhaus (2004) introduced the simultaneous lot sizing and scheduling approach in a so-called make-and-pack production environment. They investigated fast moving consumer goods industries including foods and beverages and realized that a set of technical considerations are most often observed in these businesses. By incorporating such considerations,

they could significantly reduce the complexity of production scheduling in these industries and at the same time better reflect real world conditions. Later, Lütke Entrup et al. (2005) developed MILP models based on the block planning concept for production of yogurt that investigate the effect of integrating shelf-life into production planning and scheduling. Günther et al. (2006) presented two different implementations of the block planning concept by considering a continuous representation of time. One utilizes the Production Planning/Detailed Scheduling module of the SAP APO software and the other approach is based on a mixed-integer linear programming formulation. They concluded that the suggested approach is computationally very efficient and provides the flexibility to model a variety of application specific features.

Several aspects of food distribution are investigated in literature as different variants of the vehicle routing problem with or without time windows (VRP/VRPTW). Transportation planning of dairy products is investigated based on a hierarchical approach by Adenso-Diaz et al. (1998). Considering an integrated distribution network, they make decisions on demand assignment, frequency of visiting each customer per week and vehicle routes. They considered a variant of VRPTW with the objective of minimizing the total distribution costs while clients are allocated among vendors in a fair way. Kiranoudis and Tarantilis (2001, 2002) developed a threshold-accepting based algorithm for a heterogeneous fixed-fleet VRP applied to a fresh milk and a fresh meat distribution environment with the goal of minimizing the total transportation time. Belenguer et al. (2005) considered the distribution operations of meat and developed a variant of VRPTW with the goal of minimizing the lateness in servicing customers and minimizing the total distance traveled (multi-objective). They proposed a 2-phase constructive algorithm and a tabu search based improvement algorithm to solve the resulting model. Ambrosino and Sciomachen (2007) developed an asymmetric capacitated VRP model for delivery of a combination of fresh and frozen foods through vehicles with two compartments. Hsu et al. (2007) studied a VRPTW problem for perishable food delivery with focus on customer response and energy consumption cost as a sustainability measure. Zheng et al. (2007) considered a special transportation infrastructure in Beijing city and developed a VRPTW model for fresh food delivery in cities with circular transportation networks. Osvald and Stirn (2008) investigated distribution operations of fresh vegetables and similar perishable foods. They developed a solution algorithm for the corresponding VRPTW paying attention to the linear quality degradation of products. Akkerman et al. (2010) performed a thorough survey of food distribution studies in which a separate section is devoted to transportation planning.

Integration of production scheduling and distribution planning has received a lot of attention among researchers particularly in the recent years. Chen (2009) classified and reviewed a rather considerable number of articles on general integrated production and distribution scheduling. However, there are very few studies specifically developed for the food industry. Arbib et al. (1999) developed a three-stage matching model to investigate a scheduling problem with the goal of reducing the time gap between distribution and the best-before date. Higgins et al. (2006) considered the integration of production and distribution scheduling for a sugar supply chain. Bilgen and Günther (2010) presented an integrated production scheduling and truck routing model for a fruit juice supply chain. They considered different transportation modes and described the

production system based on the block planning approach which establishes cyclical production patterns with regard to the definition of setup families.

To the best of the authors' knowledge, Chen et al. (2009) is the only study that analyses the integration of prepared food production scheduling with short-term distribution planning, including the solution of the associated vehicle routing problem. However, they used a special approach and a set of fundamental assumptions, which are not applicable to our case. While we are considering a more complex production environment with multiple production lines and sequence-dependent setup times and costs, Chen et al. (2009) assumed a production system with a single production line and no setup time and costs. Further, by assuming stochastic demand following a given distribution function, they focused on inventory and shortage costs in their model, while we face a deterministic environment in which customer orders and, as a result, production quantities are given.

3.3 Problem description

The catering industry is the main food sector dealing with production and distribution of fresh foods. Caterers are concerned with the provision of prepared food and drinks ready for consumption away from home. The main customers for the catering industry are restaurants, cafes, take-a-ways, hospitals, schools, prisons, residential homes, hotels and other premises, which order food for immediate consumption (Taylor, 2008). Catering is by far more complex than other sectors of food industry in terms of the network structure and the underlying constraints. Due to the major concern on delivering foods freshly (and most often hot), direct links between food preparation and distribution stages are prevalent, usually without any intermediate stage.

Fresh food supply chains often consist of three stages (see Figure 3.1). The first stage usually comprises batch processing of raw materials into food products, which are packaged in the second and immediately distributed in the third stage. Merging the packaging and the production stages is also frequently observed in fresh food supply chains. Production and distribution planning of fresh food, such as in the catering industry, is certainly a challenging task. The planner has, for example, to cope with a high number of food variants and sequence-dependent setup costs and times of processing equipment as well as fast quality degradation of goods.

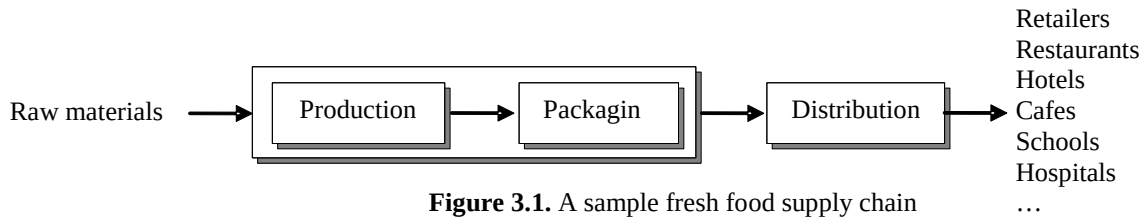

Figure 3.1. A sample fresh food supply chain

In the problem at hand, the caterer operates a production center to produce a multitude of variants of food products ordered from different service organizations. To produce orders on time and in an economical way, a batch production system is adopted to combine orders into production batches. In general, a set of orders can be combined into a batch if the respective food menus require the same temperature level and the same processing time at the ovens.

The setup cost and time in the catering company result from heating up and cooling down of ovens. Since orders need to be processed at different temperatures, the setup cost and time depend on the sequence of producing orders on ovens. Following, a list of other specifications of this production environment is presented.

- Products are produced at a single production site that operates several identical ovens. These ovens form the bottleneck of the production system.
- At the beginning of a production day, all ovens start from the turned-off state.
- A set of customer orders is known a day prior to their realization and has to be processed and delivered within certain time windows.
- Each customer order includes one type of food menu. (A food menu is defined as a unique combination of temperature requirement and processing time.)
- Idle times can be scheduled on ovens, and it is assumed that temperature of ovens does not change during their idle times.
- Food quality decay starts right after the completion of production operations and continues linearly until the delivery time.
- The time difference between the completion of production operations of each food and its delivery time represents its quality decay.

The above characteristics of the production environment result in a complex production scheduling problem with sequence dependency in setup costs and times. Moreover, prepared foods are distributed to customers through a fleet of vehicles, which is run by the catering company. Therefore, the caterer is responsible for both production scheduling and distribution decisions. The distribution operations involve transportation of highly perishable products within tight time windows at customer locations. The principal attributes of distribution planning in this company can be summarized as follows:

- The distribution problem is defined in the form of planning direct deliveries from the production site to customers (cf. Figure 3.1) without any intermediate storage.
- Vehicles are homogeneous, and they all start from and return to the central production site known as depot in the vehicle routing literature.
- Transportation costs are given based on the travel distances for delivering the orders.
- The earliest departure time of a vehicle at the production site is determined by the latest finishing times of batches to be delivered by the vehicle.
- For the delivery of orders at customer locations time windows (defined as earliest and latest visiting times) have to be considered.

The entire planning problem comprises decisions on the scheduling of production orders on the various ovens and the distribution of customer orders by use of the company’s fleet of vehicles. In particular, this production and distribution planning problem involves the following decisions:

- grouping of customer orders with similar temperature requirements and processing times and with compatible delivery and vehicle departure times into batches for joint processing at the same oven,
- assignment of batches to ovens and sequencing and time phasing of individual batches at each oven,
- determination of temperature levels which have to be realized on each oven according to the assigned batches and their specific temperature requirements,
- assignment of customer orders to vehicles and sequencing and time phasing of individual deliveries to customer locations.

The caterer aims at developing a production scheduling and distribution plan that allows to fulfill customer orders within the given delivery time windows. Major constraints arise from the available production capacities of the ovens and the distribution capacities determined by the fleet of vehicles. All production operations of batches must be completed such that the delivery due dates of the respective customer orders can be met. As for the objective of coordinating daily production and distribution activities, the caterer seeks solutions that ensure an appropriate trade-off between the monetary objective of minimizing total production setup and transportation costs and the non-monetary objective of minimizing the total quality decay of products.

3.4 Hierarchical modeling approach

Due to its complexity, the integrated production scheduling and distribution planning problem presented in the previous section is computationally intractable. Therefore, we propose a hierarchical modeling approach (see Figure 3.2), which subdivides the entire planning problem into sub-problems of considerably reduced complexity.

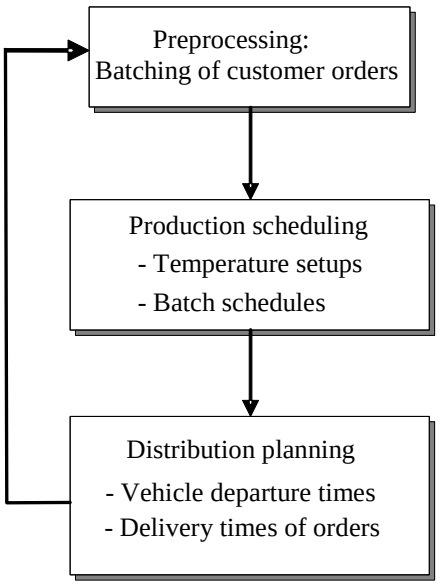

Figure 3.2. Hierarchical modeling framework

In a preprocessing stage, an aggregation procedure is applied, which creates batches of customer orders with similar temperature and processing requirements and compatible delivery and vehicle departure times (Section 3.4.1). This way, the number of entities in the production scheduling stage is considerably reduced. For processing the various batches on the ovens, a so-called block planning approach is proposed which schedules the batches according to a pre-defined sequence of temperature levels (Section 3.4.2). Given the finishing times of the batches, a heuristic solution algorithm is applied to solve the distribution planning problem (Section 3.4.3). Finally, an iterative framework is introduced to coordinate the production and distribution schedules (Section 3.4.4).

3.4.1 Batching of customer orders

The main idea behind the heuristic batching procedure is to reduce the size of the production scheduling model by grouping consistent customer orders into a set of production batches. As a result, the original problem is reduced to scheduling a considerably smaller number of entities (batches vs. orders). Customer orders can be grouped into a batch if they have the same temperature and processing time requirements and satisfy the following consistency conditions:

1. Their delivery times and their corresponding vehicle departure times do not differ by more than a pre-defined threshold value.
2. The respective food products can be processed on an oven within the given oven capacity.

Details of the heuristic batching algorithm are given in Figure 3.3. Depending on the considered case, different sorting criteria, e.g. temperature level, processing time, vehicle departure time, delivery time, and demand volume could be chosen for sorting the orders in list L. In our case, we first rank orders based on their temperature levels in ascending order. As a secondary ranking criterion, the earliest vehicle departure time of orders is chosen. An important parameter in the algorithm is the acceptable time gap between the vehicle departure and delivery times of orders that are grouped into one batch. Later in the numerical analysis (see Section 3.5), we investigate the influence of this threshold value on the final solution as well as on the algorithm performance.

```
HEURISTIC BATCHING ALGORITHM
function Batching ( i ∈ {orders})
sort all orders in list L as follows:
    Based on temperature in ascending order
    Based on vehicle departure times in ascending orders for orders with the same temperature
    while |L|>0 do
        create a new batch and set batch.Load=0
        i = first order in L
        assign i to the created batch and add i.Demand to current batch.Load
        remove i from L
        j = first order in L and set A = |L|
        while ( A > 0) do
        if ( ( j.Temperature == i.Temperature) &
        ( j.ProcessingTime == i.ProcessingTime) &
        ( j.DeliveryTime < i.DeliveryTime + threshold) &
        (ABS(j.DepartureTime - i.DepartureTime) < threshold) &
        (batch.Load+ j.Demand <= Capacity) )
            assign j to the current batch and add j.Demand to current batch.Load
            removed j from L
            j= next order in L and set A = A-1
        else
            j = next order in L and set A = A-1
        endwhile
    endwhile
Note: ABS refers to absolute value
```

Figure 3.3. Heuristic batching algorithm

3.4.2 Production scheduling

Principally, lot sizing and scheduling models can be formulated using a discrete or a continuous representation of time. In a discrete time-scale model, which is still predominant in the academic literature, the start and ending of production and setup activities are restricted by the period boundaries. Obviously, a dense time-grid is needed to adequately reflect the timing of production activities. In a continuous time based model, however, the succession and detailed timing of production activities can be reflected more realistically.

In the practical application at hand, an issue which further increases the complexity is the sequence dependency of setups. A practical approach which exploits the advantages of both the continuous time representation and the use of predefined setup sequences is the so-called block planning concept (cf. Günther et al., 2006, and Bilgen and Günther, 2010). This concept is widely

adopted in production environments with a single bottleneck stage, such as in large parts of the consumer goods industry. For the problem at hand, this method not only reflects the practical settings but also significantly reduces the complexity of the problem. In this approach, an important aspect is to define a block as a pre-set sequence of setups based on human expertise and technological requirements. Afterwards, production activities are scheduled based on the pre-defined setup sequence. For instance, in food processing industries, production managers often sequence production runs from the less intensive taste of a food product to the stronger or from the brighter color of a product to the darker.

In catering environments, a setup operation refers to setting up a certain temperature on an oven. As a result, a sequence of temperature increases and/or decreases (a block) has to be defined on each oven. However, since heating up an oven is much quicker than cooling it down, orders are scheduled on ovens based on their temperature requirements in an ascending order. Therefore, in our catering problem, we define a block as a sequence of all required temperature levels in ascending order.

Setup costs and times for heating up ovens are assumed to be additive: Heating up an oven from temperature T1 to T3 is the same as heating it up from $T1$ to $T2$ and then from $T2$ to $T3$ (with $T1 < T2 < T3$). Therefore, after defining blocks (temperature patterns), the total setup costs of an oven (production line) can be defined as the cost of heating up the line to its highest realized temperature. Accordingly, an adequate setup strategy tends to assign orders with lower temperature requirements to a line, which produces other orders with higher temperatures, thereby yielding the most economical schedules. Based on this definition, no additional setup cost is incurred if a new order can be inserted into an existing schedule without increasing the maximum temperature requirement of the schedule. However, it is essential that all orders are processed in ascending order of their temperature requirements. This constraint might enlarge the time gap between the production and delivery time of certain orders and impair the total quality measure. Therefore, an appropriate trade-off has to be sought between setup costs and the quality decay objective.

By means of the block planning concept we are able to capture sequence dependencies in setup costs and times and simplify the scheduling problem. Next, an MILP model based on the block planning concept is formulated, assuming that initial distribution decisions are given and the heuristic batching algorithm has already been applied to group orders into a set of batches. We further assume that batches are numbered such that the required temperature levels are non-decreasing. The notation is introduced in Tables 3.1-3.3.

$i, i' \in S \cup \{O, \bar{O}\}$	customer orders (S), production site ($\{O\}$:starting depot), production site ($\{\bar{O}\}$: ending depot)
$k \in J$	batches
$i \in J'_k$	customer orders processed in batch *k*
$k \in J_h$	batches requiring temperature level *h*
$v \in V$	vehicles
$l \in L$	production lines (ovens)

Table 3.1. Indices and sets

W_1, W_2, W_3	weights for cost terms used in the objective function
$c_{i',i}$	transportation cost for delivering order *i* immediately after *i'*
$c'_{h,l}$	setup cost for realizing temperature *h* on line *l*
B_i	delivery date for customer order *i* (given from the distribution model)
$X_{i',i,v} = 1$	binary parameter (given from the distribution model) indicating if order *i* is delivered immediately after *i'* by vehicle *v* (0, otherwise)
θ_i	quality decay rate of customer order *i* per unit of time
t_k	processing time of batch *k*
D_k	due time for producing batch *k*
M	sufficiently large number
g_k	setup time for producing batch *k* after batch *k-1*

Table 3.2. Parameters

$Y_{h,l} = 1$	if temperature *h* is realized on line *l* (0, otherwise)
$Z_{k,l} = 1$	if batch *k* is realized on line *l* (0, otherwise)
$F_{k,l} \geq 0$	finishing time of producing batch *k* on line *l* (with $F_{0,l}$ given)
$F'_k \geq 0$	finishing time of producing batch *k*
$SC_l \geq 0$	setup cost on line *l*

Table 3.3. Decision variables

Model formulation:

$$Min \quad W_1 \cdot \sum_{l \in L} SC_l + W_2 \cdot \sum_{k \in J} \sum_{i \in J'_k} \left(B_i - F'_k \right) \cdot \theta_i + W_3 \cdot \sum_{v \in V} \sum_{i \in S \cup \{\bar{O}\}} \sum_{i' \in S \cup \{O\}} c_{i',i} \cdot X_{i',i,v} \tag{3.1}$$

subject to

$$SC_l \geq c'_{h,l} \cdot Y_{h,l} \qquad h \in H, l \in L \tag{3.2}$$

$$\sum_{k \in J_h} Z_{k,l} \leq M \cdot Y_{h,l} \qquad h \in H, l \in L \tag{3.3}$$

$$\sum_{l \in L} Z_{k,l} = 1 \qquad k \in J \tag{3.4}$$

$$F_{k,l} \geq F_{k-1,l} + g_k + t_k \cdot Z_{k,l} \qquad k \in J, l \in L \tag{3.5}$$

$$F_{k,l} \leq D_k + M \cdot \left(1 - Z_{k,l}\right) \qquad k \in J, l \in L \tag{3.6}$$

$$F'_k \leq F_{k,l} + M \cdot \left(1 - Z_{k,l}\right) \qquad k \in J, l \in L \tag{3.7}$$

The objective function (3.1) minimizes the weighted sum of total setup costs, total food decay and transportation costs. According to (3.2), setup costs depend on the highest temperature level realized on each line. Food decay is measured by the time difference between the delivery time of an order and its production finishing time. Since each order is assigned to a batch, the finishing time of an order is the same as the finishing time of its corresponding batch. Transportation costs are calculated based on the traveled distance of vehicles for visiting all customers. In this model, the transportation part of the objective function is a constant given as the solution to the distribution problem. However, for the sake of uniformity, we keep this term in the objective function. The objective function consists of monetary as well as of non-monetary terms. Thus, an appropriate trade-off is pursued between cost components and the quality measure in the numerical tests. Constraints (3.3) prevent realization of a batch on a line unless its corresponding temperature level is used on that line. Constraints (3.4) guarantee that each batch will be scheduled on one line. Constraints (3.5) indicate the relationship between production finishing times of two successive batches. In these constraints, the processing time of a batch t_k depends on the processing time of orders assigned to it by the heuristic batching algorithm. Constraints (3.6) ensure that when a batch is produced on a line, its production finishing time on that line is smaller than its due time. It should be noted that due to the negative sign of the F-variables in the objective function orders are scheduled as late as possible. Since a preliminary distribution plan with the departure time of vehicles is assumed to be given, constraints (3.6) impose a proper upper bound on the production finishing time of each batch on each line. Constraints (3.7) determine the production finishing time of each batch depending on its assigned production line. Variable domains are already given in Table 3.3 with the definition of the decision variables.

The application of the block planning concept and the heuristic batching algorithm significantly simplifies the production scheduling problem. As a result, the developed model is easy to solve using standard optimization software.

3.4.3 Distribution planning

Given the production scheduling decisions, the distribution problem determines the vehicles' tours and schedules. It seeks solutions that minimize a trade-off between transportation cost and the quality decay component of the objective function. Further, it ensures that the developed production schedules are observed in determining the vehicle tours. The distribution problem in our catering case can be formulated as a variant of the vehicle routing problem with time windows (VRPTW). Since it is a classical model (with a different objective function) and we aim at solving this problem using a heuristic approach, we do not present the mathematical model for the distribution problem.

Several heuristic algorithms were developed to deal with the VRPTW, which mainly work on the exchange of two or a few nodes between routes. Such node exchange algorithms can be considered as small neighborhood search methods. However, it is believed that such small neighborhood explorations, even when combined with meta-heuristic methods, are not effective in avoiding local optimality thereby making it difficult to jump from one promising area of the solution space to another, when a tightly constrained problem is solved (Ropke and Pisinger, 2006). In the following, we develop a large neighborhood search (LNS) algorithm that obtains good quality solutions for this problem.

The LNS algorithm was first applied to the VRPTW by Shaw (1997) showing its superiority over other heuristic methods. This algorithm iteratively relaxes and re-optimizes the current solution. In VRPTW applications, the relaxation phase refers to removing a certain number of orders from the available routes and the re-optimization stage inserts them back in the feasible positions based on some optimization criteria. Therefore, in designing an LNS algorithm, the number of orders to remove in each iteration (denoted by q) and the removal and insertion operators must be determined. In this paper, we adopt two operators for removal and perform the insertion based on the greedy insertion method. The first removal operator is taken from Shaw (1997) and described in Figure 3.4.

Shaw's removal procedure
1. *randomly* choose one of the orders from the routes to be removed
2. *while* not enough orders are removed *do*
2.1 $\boldsymbol{i}$ = an order chosen randomly from the set of removed orders
2.2 *Rank* all unremoved orders based on their relatedness to order $\boldsymbol{i}$
2.3 $\boldsymbol{r}$ = a random number in **[0,1)**
2.4 *Remove* the order which is $\boldsymbol{r}^{\boldsymbol{i}}$ of the way through the rank
3. *endwhile*

Figure 3.4. Shaw's removal procedure

The relatedness measure $R_{i',i}$ between orders i' and i is defined in equation (3.8). This equation determines the relatedness of every pair of orders based on four criteria, namely travelling cost $c_{i',i}$, delivery time difference $|B_{i'} - B_i|$, being served by the same vehicle ($T'_{i',i} = 1$) or not ($T'_{i',i} = 0$), and load difference $|d_{i'} - d_i|$. The corresponding weights for these criteria are set to $\alpha = 0.75$, $\beta = \delta = 0.1$ and $\gamma = 1$ based on the results of preliminary test runs.

$$\frac{1}{R_{i',i}} = \alpha c_{i',i} + \beta |B_{i'} - B_i| + \gamma T'_{i',i} + \delta |d_{i'} - d_i| \tag{3.8}$$

Further, we consider a simple worst-case removal operator as a second removal operator to diversify the search scope. This operator removes orders based on their influence on the objective function. First, a random number is generated and is compared to a parameter *p*. If the generated number is less than *p*, Shaw's operator is applied. Otherwise, the worst case operator is chosen. Considering two different operators incorporates a random component into the algorithm while orders are still removed systematically. The appropriate value of *p* depends on characteristics of each case study. In the case at hand, we set *p* to 0.75 as it results the best solution in our numerical implementations. In each operation of the LNS algorithm, the greedy insertion operator ranks the removed orders based on their influence on the objective function and selects the one which increases the total costs the least. In order to increase the feasible solution space for the algorithm, time-windows at customer locations are considered as soft constraints that can be violated subject to high penalty costs. The developed LNS algorithm stops after a certain number of iterations and returns the best incumbent solution as described in Figure 3.5.

```
Large Neighborhood Search algorithm
function LNS ( s ∈ {solutions} , q)
  while stopping criterion is not met do
        s'= s
        r = a random number in [0,1]
        while q orders have not been removed do
              if ( r < p)
                    remove one order from s' based on Shaw operator
              else
                    remove one order from s' based on worst case operator
        endwhile
        reinsert removed orders into s' based on greedy insertion operator
        if ( f(s') < f(s) )
              s= s'
  endwhile
  return s
```

Figure 3.5. Large Neighborhood search algorithm

3.4.4 Iterative solution procedure

To solve the integrated production and distribution problem, an iterative solution framework is developed as illustrated in Figure 3.6. We initialize the solution algorithm by assuming a set of very early production finishing times as the starting point. Afterwards, an iterative procedure is employed starting with the distribution problem and followed by production scheduling. The main reason for this initialization is that the production schedule has a large solution space, as every set of production finishing times can be converted into a feasible schedule by advancing production activities to an earlier point in time. Therefore, assuming early production finishing times for all production activities is a reasonable assumption in order to provide the distribution problem with a high degree of flexibility in designing optimal routes. On the other hand, the distribution problem is facing tight time windows at customers, which limits the possibility of accepting any arbitrary distribution pattern as the starting point. Therefore, different starting points are utilized to initialize the algorithm by different early production finishing times.

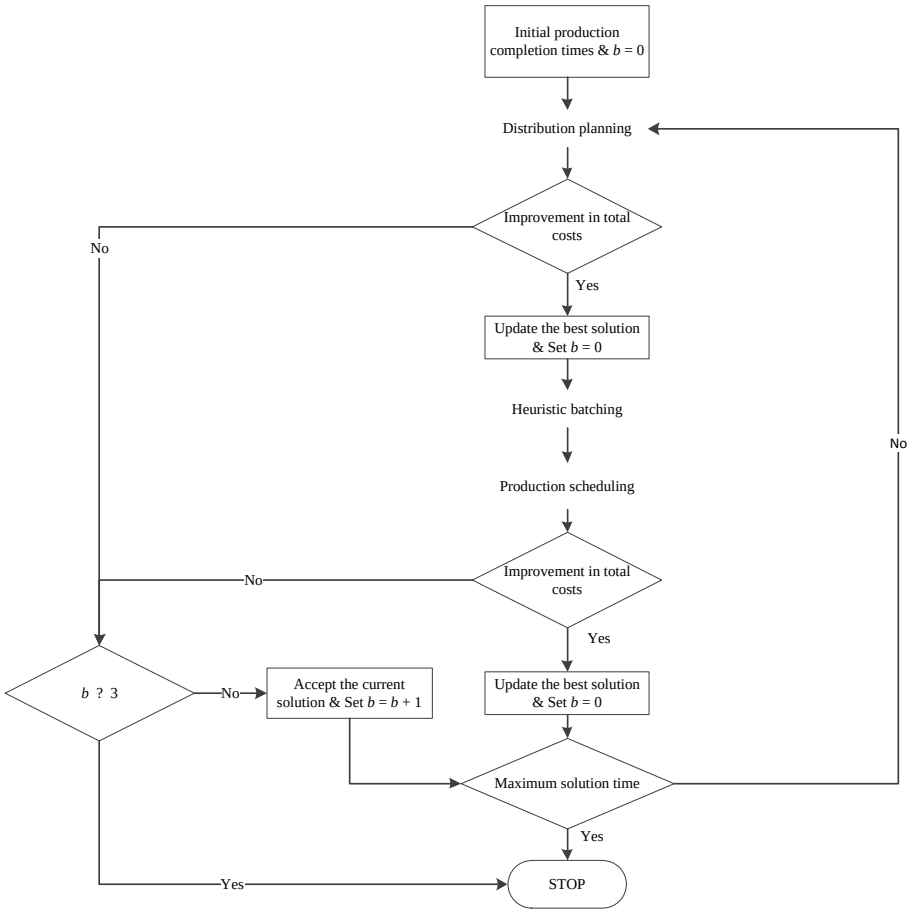

Figure 3.6. Iterative solution method

To stop the algorithm, we used two termination criteria: (1) maximum solution time, as a common stopping criterion in designing iterative algorithms, and (2) maximum number of iterations in which the model cannot achieve any improvement in the objective function. The reason for the second criterion is that either a new solution of the heuristic batching algorithm or a degenerate solution of the production scheduling problem is obtained. At each iteration, the heuristic batching

algorithm may find a new set of batches resulting in a different solution space of the production scheduling problem. Therefore, it re-initializes the algorithm with a new initial solution, which may lead to further improvements in total costs in subsequent iterations. Also, in the case of problem degeneracy, the production scheduling problem may find solutions with the same objective function. Therefore, we let the algorithm continue unless the same objective value is obtained b times in a row (with b being the maximum number of acceptable iterations without any improvement in the objective function). In the numerical investigations, we noticed that setting b to be 3 is sufficient for our case study.

Figure 3.7 illustrates one iteration of the solution algorithm showing how the production scheduling problem is simplified by using the heuristic batching algorithm and the decomposition into the production and distribution problem. This figure considers a simple instance with eleven orders, three temperature levels and three ovens. For simplicity, all order processing times are assumed to be the same and a single threshold value of five time units is used for both delivery and departure time-differences. Further, we assume that all order sizes are 3 units and the capacity of the ovens is 9 units.

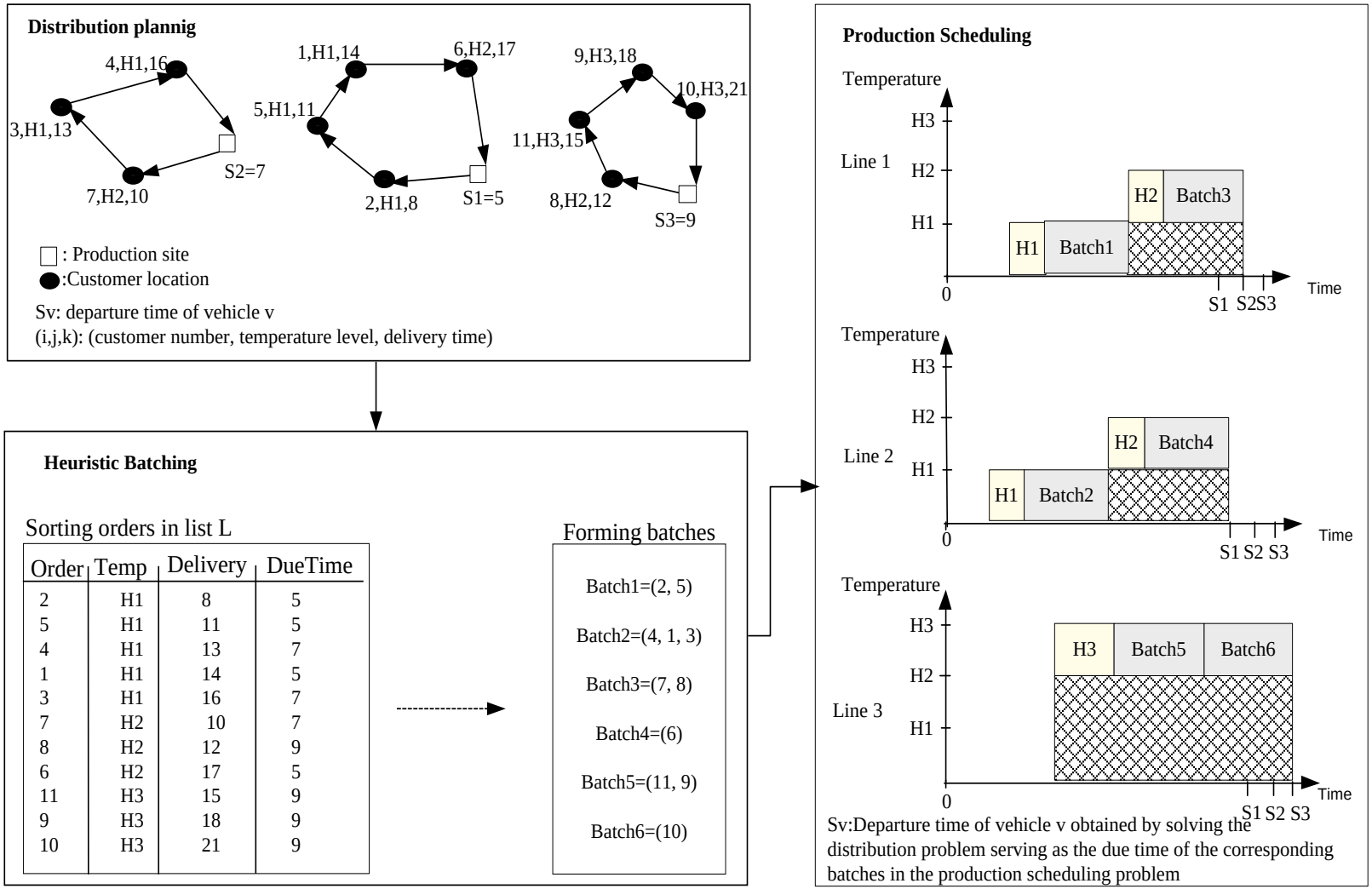

Figure 3.7. An illustrative example of the solution method

Given a set of production schedules, the LNS algorithm is called to solve the distribution problem generating vehicle routes and departure times as depicted in the first box of Figure 3.7. As a result, vehicle departure times (*Sv*) and customer delivery times are determined. These variables serve as input in running the heuristic batching algorithm, which mainly comprises two steps shown in the second and third box. In the second box, orders are sorted in a list (*L*) in ascending order based on their temperature requirements and their due times (their corresponding vehicle departure times). The list of sorted orders, *L*, represents the priority of orders for being grouped into batches. The third box shows the grouping of orders into batches based on the consistency conditions in the following way. The first order in *L*, order 2, is selected and removed from the list to form batch 1. Then, considering the two combination conditions of the heuristic batching algorithm (see Section 3.4.1), the batching procedure combines consistent orders from the top of the list into batch 1. Next, it generates a new batch (batch 2) which includes the first order that cannot be combined with batch 1, and combines the remaining consistent orders with this order with regard to the two combination conditions. In the illustrated example, first the consistency of order 5 with order 2 is checked. Since its processing time and temperature requirement are the same as of order 2, it is consistent with order 2. Besides, its delivery and departure times are closer than 5 time units to those of order 2 (condition 1) and the aggregate load of the batch does not violate the oven capacity (condition 2). Therefore, order 5 is removed from the list and added to batch 1. However, the remaining orders cannot be combined with order 2. For example, order 4 cannot be added to batch 1 because its delivery time is not closer than 5 time units to that of order 2 (condition 1 is violated). Therefore, batch 2 is created for the first remaining order of the list, order 4. Later, order 7 cannot be added to batch 2 because its temperature requirement is not the same as that of order 4. The algorithm continues until all orders are grouped into a set of batches. In this small instance, the algorithm reduces the number of items to be scheduled from 11 to 6.

Then, the production scheduling problem is solved for the generated batches such that each batch is finished before its due date. (The due date of a batch is the departure time of the vehicle that carries orders of that batch). As shown in Figure 3.7, lines 1 and 3 start later than line 2. This is because the due dates of their batches allow them to postpone the production time to reduce the time gap between the production and delivery times of orders. Finally, the resulting production schedules are released into the distribution module as input for the next iteration, where the production finishing times provide bounds on the vehicle departure times.

3.5 Numerical results

In this section, the proposed planning approach is evaluated through a number of numerical tests. We developed a main test set consisting of 200 orders based on the real setting of the catering company at hand. Three additional test sets are derived from the main set for testing the algorithm on different problem sizes (see Section 3.5.1). To obtain problem instances, we modified Solomon's R201 test instance (Solomon, 1987) regarding customer locations and delivery durations. In case 1 and 2, Solomon's R201 data are used by considering the first 50 and 100 orders. In case 3 and 4, the first 100 orders from the second test instance are copied and location data are randomly generated for the next 50 and 100 orders such that they locate in the defined area of the first 100 customers.

Customer order size is randomly generated in the range of 40 to 60 units based on a uniform distribution function. Orders are randomly assigned to one of the available temperature levels, processing times and decay rates. Production setup costs and times are determined based on the difference in temperature levels while transportation costs depend on the distance between customer locations. Further, setup costs, transportation and quality decay costs are weighed 0.2, 0.3 and 0.5, respectively, in the objective function. We also determined the number and capacity of ovens and vehicles based on the generated customer demand. Furthermore, to better represent the company's case, we set the same time window of 11 a.m. to 1 p.m. for delivering all orders. Table 3.4 briefly presents the other production and transportation parameters used in the different test sets.

Test set number	1	2	3	4
# of orders	50	100	150	200
# of ovens	2	3	4	5
# of vehicles	8	15	20	25
# of temperature levels	3	4	4	5
# of processing times	3	3	3	3
Decay rates	{3,6,9}	{3,6,9}	{3,6,9}	{3,6,9}

Table 3.4. problem parameters

To implement the algorithm, we coded the iterative framework, heuristic batching and LNS algorithm using VC++ 6 and modeled the production scheduling problem with ILOG OPL 6.1.1. CPLEX 11.2 was used as the solver. All programs are run on a PC with Intel P4 3.2GH CPU and 1 GB RAM.

In designing the LNS algorithm, two parameters are to be set: The number of nodes to be removed and reinserted at each iteration (q), and the number of iterations. Selecting a large value for q will lead to a redesign of a large part of available routes at each iteration. However, since a very myopic operator is used for the insertion procedure, the chance to generate a feasible solution would be very small. Further, such setting inflates the computational time. On the other hand, selecting a very small value for q will limit the chance of exhaustively exploring the potential neighborhoods. Based on the problem settings and time windows, we found a value of 3 to be appropriate for q. The number of iterations is set to 8000 as the algorithm rarely achieves a significant solution improvement thereafter.

Since the selection of a certain starting point might affect the way the algorithm proceeds in the next stages, we considered different sets of initial solutions. In determining the starting points for the algorithm, we took into account the requirements of the distribution problem in terms of the time-windows at customer locations. As a result, different sets of potential earliest and latest production finishing times are considered. For each set, once we ran a test instance by assigning an identical production finishing time to all orders. Further, we produced other sets of starting

solutions by assigning different production finishing times to different orders as random numbers between the potential earliest and latest finishing times. For running the numerical analysis, we chose the starting solution set, which produced the best results.

The next two parameters that need to be determined are the threshold parameters in the heuristic batching algorithm. They influence the number of batches to be generated and significantly affect the performance of the algorithm. We set the threshold parameters to a value of 70 minutes and investigate the sensitivity of these values in Section 3.5.3. Finally, we should mention that we limited the total solution time to 40 minutes through which most problem instances are solvable, regardless of the chosen threshold values.

The principal questions addressed in the numerical studies are as follows:

1. What is the effect of integrating production and distribution decisions?
2. How does the perishability of products impact the overall solution quality?
3. How do different parameter settings for the heuristic batching algorithm influence the final solution?
4. How can an appropriate balance be found between the conflicting objectives of minimizing quality decay and minimizing setup and transportation costs?

3.5.1 Sequential vs. integrated planning approach

As a benchmark, we consider a sequential approach similar to the procedure currently used by the company. This approach performs the production and distribution planning tasks separately and only based on their related cost terms, i.e. the quality decay is not optimized in this approach. Production activities start at the beginning of the shift every day (6:00 am), and we consider a realistic fixed due time (10:00 am) based on staffs' experience to finish all production activities. To determine the production schedule in the sequential approach, the concept of block planning is applied. We first run the heuristic batching by only considering combination condition 2 of the heuristic batching procedure. After running the heuristic batching, production schedules are determined imposing constraints on the distribution problem. Then, the distribution problem is solved with regard to the established production schedules.

Table 3.5 shows that the relative improvement in the quality decay of the integrated approach over the sequential approach increases considerably with problem size. In the problem instance with 200 customers (main problem), integration resulted in a significant decrease of 40.9% in quality decay. At the same time, the increase in transportation and production costs is about 18.7%. The magnitude of quality improvement justifies the integrated planning approach despite the increase in production and transportation costs. In problems with a small number of orders, the number of consistent orders that can be combined into a batch decreases considerably. The heuristic batching procedure hence creates a large number of small-sized production batches. Therefore, the oven's capacity is not well utilized leading to an increase in makespan. This leads to high quality decays in batches that must be produced early. However, the algorithm still works considerably better than the sequential approach for all problem instances. In Section 3.5.3, we further investigate other settings

that yield a large number of small batches and show how they impair the quality of the final solution.

Problem size	50	100	150	200
Relative change in the quality decay value	-18%	-27.7%	-36%	-40.9%
Relative change in transportation and production costs	+12.3%	+16.5%	+18.3%	+18.7%
Relative change in objective function	-9.5%	-14.7%	-22.3%	-28.2%

Table 3.5. Comparison of the integrated vs. the non-integrated approach

3.5.2 Integrated decision making and product characteristics

We now analyze how the degree of product perishability influences the importance of integrated decision making. In this regard, three variants of the main problem are analyzed each with all products having the same decay rate of 3, 6 and 9, respectively. It can be expected that a higher reduction in the objective function value is conceivable by integrating production and distribution decisions when products are more perishable. Figure 3.8 shows that the relative objective value improves more when products are more perishable. However, in our problem instance, the final improvement for decay rates 3 and 6 is almost identical.

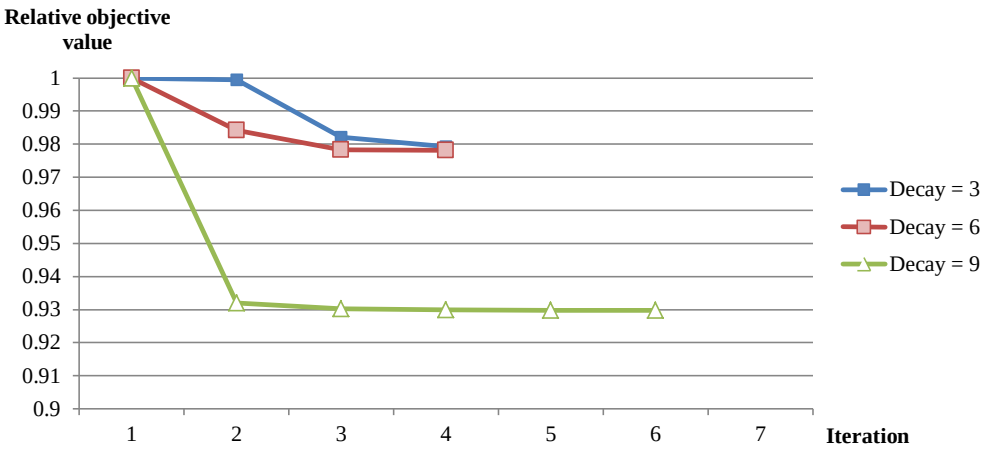

Figure 3.8. Decay rate analysis

3.5.3 Parameter settings in the heuristic batching algorithm

As explained in Section 3.4.1, the heuristic batching algorithm uses threshold parameters to identify consistent orders that can be grouped into batches. Generally, a threshold parameter defines a certain acceptable distance from a base value of a parameter. In this section, we analyze the effect of threshold parameters by running the main test set under different values for both the delivery and

departure thresholds. We tested a range of values between the two extreme settings of 0 and 120 minutes for the threshold parameters. In our main problem instances, the value of 120 minutes for the threshold parameters is an extreme setting because the total time-window over which a customer may be served is between 11 a.m. and 1 p.m.

Setting the threshold value to zero prevents order combinations. Hence, orders have to be scheduled sequentially based on the list L (see Figure 3.3). In such situation, since the number of production lines is limited, early scheduling of the first batches is unavoidable. This solution is indeed very poor in terms of quality decay. In the other extreme, setting a too large threshold value reduces the number of batches, but combines orders that better not be produced together. Thus, some orders will again be produced earlier than necessary and the quality decay will be high. As illustrated in Figure 3.9, the threshold parameters mainly influence the decay cost, while other objectives are impacted much less. We found the best results using a value of 70 minutes for the threshold. The figure also depicts that, in general, high threshold values are more appropriate than very low values. Although a high threshold may combine more orders than necessary, a too low threshold value has a stronger impact on decay costs by generating too many batches and increasing the total production time. Such extra production time forces the whole schedule to start earlier, thus yielding a higher quality decay cost.

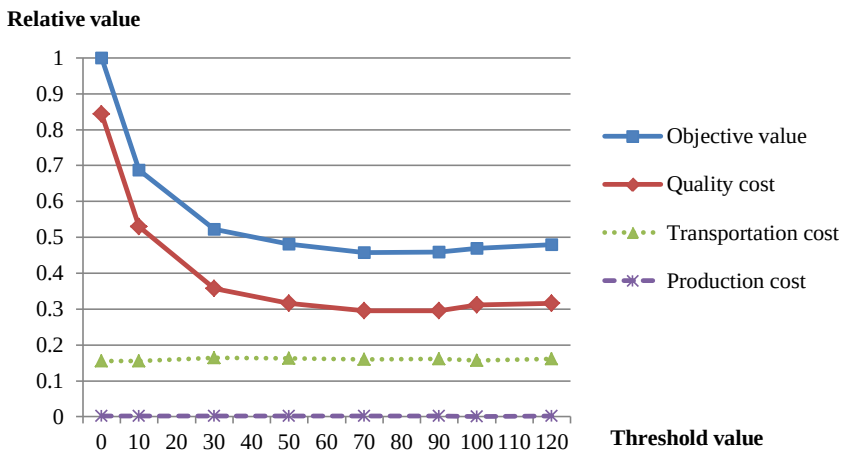

Figure 3.9. The effect of threshold value

The total production time can be reduced to a certain extent by setting higher threshold parameters. On the other hand, a direct relationship is inherent between the length of processing times and the total production time such that the longer the processing times are, the longer will be the total production time and vice-versa. Therefore, in a problem instance where all parameters are fixed, if processing times are increased, the optimal decision is most likely to increase the threshold values to compensate for the newly added production times.

3.5.4 Finding an appropriate trade-off between quality decay and other cost terms

The last part of the numerical analysis addresses the question of how an appropriate trade-off can be found between quality decay and production and transportation costs. To investigate the relationship between these conflicting objectives, we solved the main test problems with five

different weights for decay cost and considered equal weights for production and transportation costs. In our problem setting, setup and transportation costs are relatively smaller than decay cost. Therefore, by increasing the decay cost weight the model compromises on the setup and transportation costs and adapts distribution decisions accordingly to improve the quality term. In Figure 3.10, the corresponding unweighted values of quality decay, production and transportation costs are compared. As illustrated in this figure, by increasing the decay weight from 0.1 to 0.5 a continuous decrease in the decay objective can be achieved without exorbitantly increasing total transportation and production costs. The two dashed lines represent the share of production and transportation in the total costs.

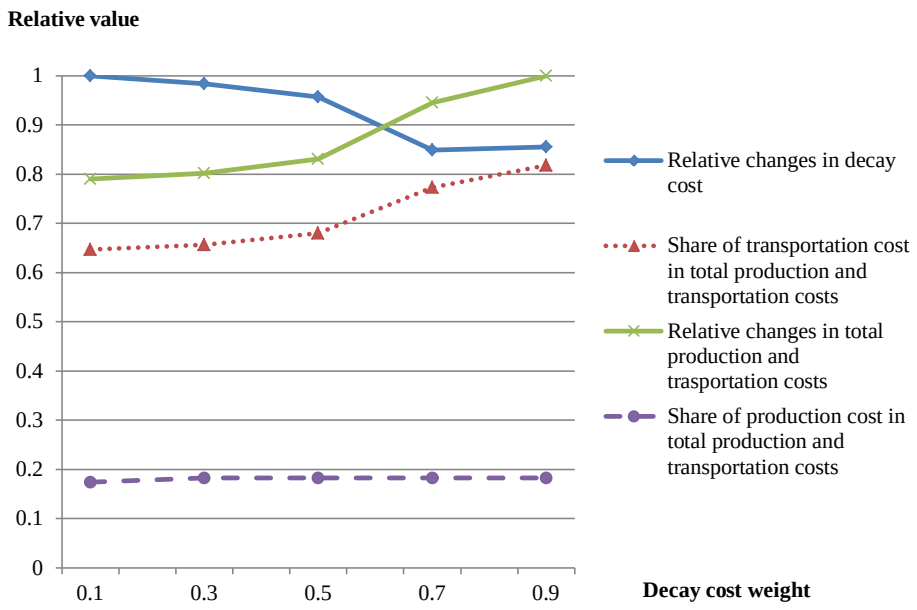

Figure 3.10. Decay weight analysis

By increasing the decay weight beyond 0.5 still a major improvement in food quality is achieved. However, the achieved improvement in food quality goes along with a significant increase in the other cost terms. Thus, the cost related consequences of such quality improvement should be carefully discussed with managers of the company for setting the quality decay weight in such situations.

One possibility for further improving quality cost without increasing the production and transportation costs would be to change the block definition. Currently, production blocks are defined based on an incremental temperature pattern, because heating up ovens is much easier than cooling them down. However, if we could change this technical limitation, we could for example obtain block definitions that allow for cooling down ovens at the end of their production schedules. Such consideration could significantly increase the flexibility of the production system.

3.5.5 An alternative quality improvement approach

As an alternative approach, we first run a pre-optimization procedure, through which a problem instance is solved with quality decay being optimized by a min-max function. Contrary to the

previous approach in which the difference between the highest and lowest product quality might be very large, the new method ensures that all customers enjoy a minimum level of quality. In order to implement this approach we introduce a new decision variable and a new set of constraints as follows:

$\varphi \geq 0$ Maximum quality decay among all delivered products

$$\varphi \geq \sum_{\forall k \in J} \left(B_i - F_k'\right) \cdot \theta_i \qquad \forall i \in S \qquad (3.9)$$

Further, we modify the objective function accordingly to incorporate the newly defined variable as follows:

$$Min \quad W_1 \cdot \sum_{l \in L} SC_l + W_2' \cdot \varphi + W_3 \cdot \sum_{v \in V} \sum_{i \in S \cup \bar{O}} \sum_{i' \in S \cup O} c_{i',i} \cdot X_{i',i,v} \qquad (3.10)$$

Constraints (3.9) set φ as the maximum quality decay among all delivered products and equivalently the minimum quality level perceived by customers. Further, the quality component is defined in the objective function (3.10) such that it minimizes the value of φ resulting in a better lower bound on the quality level. The same analysis as in section 3.5.4 is required to find the appropriate weight W_2'.

In a pre-optimization stage, constraints (3.9) are added to both the production scheduling and transportation planning problems, and they are solved with the modified objective function (3.10) considering φ as a decision variable. Afterwards, the modified problem is solved again, with objective function (3.1) considering the value of φ as a given parameter. This parameter provides an upper bound on the quality decay that a customer might observe. To investigate the influence of the pre-optimization stage, we solved the main problem instance (with 200 customers) and compared its results with those of the previously introduced method. Table 3.6 presents the ratio of the results achieved when the pre-optimization stage is considered versus the option without pre-optimization. The comparison reveals a 14% improvement in maximum perceived quality decay (minimum quality level) and a 4% improvement in minimum perceived quality decay for a virtually unchanged total quality decay (increase of 0.01%).

	Impact of the pre-optimization step
Total quality decay	1.0001
Maximum perceived quality decay	0.86
Minimum perceived quality decay	0.96

Table 3.6. Comparative results between with and without the pre-optimization stage

3.6 Summary and conclusions

Among several specific characteristics of fresh food industry, the quality concern is perhaps the most prominent one. In the fresh food industry, food quality is strongly influenced by the two interrelated stages of production and distribution. However, due to the complexity of these problems, research attention is usually limited to solving them separately thereby neglecting their strong interrelation. Being aware of such complexity, we incorporated some simplification steps to develop an integrated approach for production scheduling and distribution planning of fresh foods such that the model is still a good representation of the real world situation. To this end, we focus on decomposing the production model into two successive stages and designing a solution algorithm to appropriately integrate them with the distribution model. As a result, we were able to reduce the problem complexity considerably and to solve the integrated problem in a reasonable time.

Results of our numerical investigation indicate that the integrated approach significantly improves food quality without considerably increasing production and distribution costs. Further, we showed that an appropriate minimum quality level can be guaranteed through our alternative approach which imposes a measure of balance among customers service levels. We also showed that the improvement in food quality is larger when foods are more perceptible to quality decay. However, focusing on food quality improvement is sound and commercially viable only as long as the total costs do not exceed certain limits. We took into account the particular characteristics of a catering problem in developing the mathematical model, designing the algorithm, and setting the parameters. The developed models reflect major issues arising in catering industry based on the explained case study. Nevertheless, their main features are also relevant for other types of fresh food industries like bakeries. Analyzing more complex cases with multiple producers is the subject of our future research.

Chapter 4. Integration of workforce planning with production and distribution

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Abstract

The foodservice sector is associated with a limited possibility of storing foods due to shelf life restrictions, a labour-intensive production environment with various skill requirements, low profit margins, and an extensive set of regulations and expectations regarding the quality of meal provision. Inspired by a municipal foodservice case in Denmark, we discuss the main challenges in the design and operations planning for the foodservice sector explaining the necessity of taking an integrative approach. Accordingly, a hierarchical planning methodology is developed focusing on integrating planning of the required multi-skilled workforce with the planning of production and distribution. Decisions are classified as design and operational depending on their aggregation level and formulated as generic mathematical models, which are applicable to similar cases. The developed models are subsequently solved in a case-tailored iterative solution procedure. The numerical results presented in the paper show the contribution of our integrative approach in improving performance measures at the case municipality, and provide managerial insights into the problem.

4.1 Introduction

Delivery of meals from institutional kitchens is becoming more and more important, particularly for nursing homes, meals-on-wheels providers, schools and kindergartens. This is especially true in western societies where the demographic development is towards an increasing number of elderly who live in nursing homes. For instance, in Denmark, citizens of over 65 years of age or below 6 comprise about 21% of total population of Denmark (Statistics Denmark, 2010), and this figure is expected to increase to about 26% in 2023. Such significant growth indicates the potential role that prepared meal delivery plays in the daily food intake in the Danish society. Next to the growing quantity of meals delivered through institutional kitchens, concerns about the quality of the food provided through these centres are also increasing. For instance, the growth in implementation of feedback routines among nursing homes on acceptability of food services from 1995 till 2003, reported by Mikkelsen *et al.* (2007), indicates an increasing concern about the quality of meals delivered to the elderly. In addition, further legislative incentives are recently put into action to increase the quality of served meals in these institutions.

With regard to the main production processes, meal production environments can be classified into conventional (cook-hot-hold), cook-chill, and cook-freeze production systems (Rodgers, 2005).

In cook-chill and cook-freeze environments, the time between production and consumption of meals is extended, leading to a situation where meals are produced, stored, transported, and possibly stored again before they are consumed. Such considerations increase the need to integrate the planning of production and distribution operations.

Prepared meal delivery to nursing homes and kindergartens is usually carried out under limited public funding. Especially in today's aging society, the total budget to allocate to prepared meal delivery is an important political subject. In Denmark, the supply of food to the elderly and school children is organized on a municipal level. Therefore, each municipality has to decide on the budget it allocates to best design and operate its meal delivery system. Moreover, the elderly and school children are expected to receive high quality food despite the limited available funding. Therefore, optimization of the production and distribution operations, leaving a larger share of the budgets to invest in high quality ingredients, is essential in municipal foodservice operations. Besides, due to the broad range of required skills to perform different production operations in this industry, the production capacity is often limited by the availability of skilled labour. As a result, hiring and assignment of skilled labour to production operations should be made in coordination with production and distribution plans.

The aim of this paper is to provide decision support models for the design and operations planning of municipal meal production and delivery systems. The contribution of our work is a planning approach integrating the planning of multi-skilled workforce with production and distribution operations in the foodservice industry. To this end, we first organize the related decisions into long-term and short-term decisions and then develop a generic hierarchical modelling approach for this problem. The developed models are subsequently solved through an iterative solution framework, connecting the long-term and short-term decisions, and handling the potential infeasibilities and sub-optimalities. The solution quality of the iterative framework is further strengthened by taking the customer order arrival process into account. Numerical analyses, inspired by a Danish case municipality, indicate the value of integrative planning approach for the foodservice industry.

The remainder of this paper is organized as follows. In the next section, related research will be discussed. Then, Section 4.3 presents the problem description in more detail through explaining the case study. In Section 4.4, the modelling framework and the mathematical representation of the problem are discussed. The solution approach is explained in Section 4.5 followed by the numerical analysis. Finally, the paper concludes and the future research directions are presented.

4.2 Related research

Coordination of production and distribution operations often leads to significant improvements especially for industries where the possibility of inventory storage is quite limited due to product or market characteristics. Chen (2010) reviewed and classified integrated production and distribution studies on the basis of their modelling and solution algorithm characteristics. Such integration is very important in the food industry, due to the specific characteristics of food products, especially shelf life considerations. Lowe and Preckel (2004) and Ahumada and Villalobos (2009) extensively

reviewed planning problems in the agricultural industry focusing on production and distribution of crops. As one of their key findings, they conclude that the literature suffers from insufficient research on integrated planning problems in the agro-food industry. Later, Akkerman *et al.* (2010) presented a thorough review of quantitative approaches in food distribution management, also including integrated production and distribution problems. They focus on the activities after the provision of food ingredients, and conclude that the available studies have mainly focused on retail applications apart from a few exceptions.

Among the limited research in the foodservice industry, integrated meal production and distribution planning is first analyzed by Chen *et al.* (2009). They considered a centralized single-resource production environment with stochastic demands. Their aim is to maximize the expected profit including a quality-related cost component. Later, Farahani *et al.* (2011) considered a more general case with multiple production resources and setup costs. For the production planning problem, they employed the block planning concept, previously investigated in food production scheduling by Günther *et al.* (2006), and developed a heuristic method to solve the resulting production and distribution problem. They already illustrated that an integrative approach can lead to considerable improvement of the quality of the prepared meals without a significant increase in the total costs.

The previously discussed work considers production capacity in terms of physical production equipment. In the foodservice industry, labour is however often the key capacity factor. Due to the broad range of skills required to perform different operations, hiring the correct number and mix of employees to be assigned to different production operations is an important and challenging task. Workforce planning and scheduling encompasses a wide scope of well-researched academic problems ranging from strategic decisions on the number of required employees over a long horizon studied as early as Abernathy *et al.* (1973), to recent studies of the short-term scheduling of individual employees, *e.g.*, Stolletz (2010). In our study, we aim at determining the optimal number of staff to be assigned to production tasks on the basis of the requirements of the tasks and the skills of the staff. This locates the workforce planning side of our work between the categories of strategic workforce planning and operational task assignment as identified in an extensive review by Ernst *et al*. (2004). As also presented in Ernst *et al*. (2004), several authors (Love and Hoey, 1990; Loucks and Jacobs, 1991; Goodale and Thompson, 2004; Thompson and Goodale, 2006) researched workforce planning and scheduling in the foodservice industry. However, all these studies focus on the operational problem of developing tour schedules for individual staff. Among the related studies in other industries, Grunow *et al.* (2004), Wirojanagud *et al.* (2007), Fowler *et al.* (2008), and Rong and Grunow (2009) are closer to our problem definition. Grunow *et al.* (2004) investigated the problem of planning and scheduling multi-skilled workforce for running the clinical studies in pharmaceutical industry through developing a two stage hierarchical model. Fowler *et al.* (2008) extended the work by Wirojanagud *et al.* (2007) through developing heuristic algorithms for general workforce planning problem with worker differences focusing on the influence of cross-training programs on increasing workforce flexibility. Rong and Grunow (2009) investigated the problem of planning permanent and temporary workforce in air cargo terminals.

This paper takes a quantitative approach to re-structuring and optimizing foodservice operations. To do this it takes an integrated approach to the planning of workforce, production and distribution operations. As such, our work contributes to the literature on foodservice management by analysing this problem for a typical foodservice case representing a multi-site, multi-stage meal production and distribution system, serving a variety of different customers.

4.3 Problem description

In defining this problem, we got inspired by a foodservice case in a Danish municipality. The case exhibits several characteristics that are typical for the foodservice sector. The municipality in our case study has about 50,000 inhabitants and two nursing homes with large-scale kitchens. These nursing homes prepare food for the elderly who live there and also provide a significant number of elderly people living in their own homes with a meals-on-wheels service. Furthermore, since the municipality is expecting an increase in the number of the elderly, it is opening an additional nursing home. However, this nursing home will not have its own kitchen and will be supplied with food from the existing kitchens. Next to these food arrangements for the elderly, the government of Denmark recently decided that lunch meals must be provided for all kindergartens, and this must also be organized on a municipal level. In light of these developments, the case municipality needed to re-design its meal production and delivery system and optimize its operations. This problem setup, with several production locations producing highly perishable products and redesign discussions due to an increasing demand is typical for Danish municipalities, and arguably for the foodservice industry in general.

The two nursing home kitchens are responsible for the provision of meals to the following four customer groups:

1. Residents of nursing homes with kitchens,
2. Residents of nursing home without kitchens,
3. The elderly that are provided with food at their homes (meals-on-wheels customers),
4. Children in kindergartens.

The first customer group is served on a daily basis in the respective nursing homes. The remaining customers are provided with a menu indicating the meals that can be ordered for each day for a period of several weeks. Moreover, some customers may not order meals for some days, resulting in different capacity requirements over different days. In our case, the menu is designed such that each meal is provided not more than once in a 14-day period. Meals are prepared in the central kitchens, then chilled, stored and sent out to these customers; there, the meals can again be stored for some days before consumption. Thus, customers of groups 2, 3 and 4 do not have to be provided on a daily basis. Instead, their orders of several days can be combined and delivered through a single delivery to reduce distribution costs as long as certain quality requirements are met. Here, the quality of the food is measured based on the remaining share of its shelf life. Thus, the municipality prefers to deliver the meals as fresh as possible, to obtain logistical benefits and also improve the customer experience.

Kitchens work seven days a week. Production operations can be performed throughout the day, while transportation of foods is only performed before lunch time to be able to include the day's meal. In order to produce meals the following series of sequential production activities has to be performed:

1. Preparation activities, such as cleaning and cutting of raw materials,
2. Processing activities, such as the actual cooking of meals, and
3. Packaging activities, such as vacuum packaging of meals.

The volume of work needed to carry out a production activity depends on the individual meals. For instance, the preparation activity might include much more delicate cutting operations in one meal than in another one. To perform its production activities, each kitchen hires a number of temporary and permanent staff. To cover demand peaks, the kitchens do not work with overtime, but they can hire temporary staff. However, as the recruitment cost of temporary staff is significantly higher than the permanent staff, the number of permanent and temporary staff should be decided carefully. The staff is hired based on the required skills as exemplified in Table 4.1. Kitchens can also run training programs to help their permanent workers obtain new skills. For instance, the operation of the packaging equipment requires additional training. Thus, this activity can only be done by staff with skill 3 in Table 4.1. On the other hand, preparation activities are rather simple and might be performed by all staff (skills 1, 2 and 3 in Table 4.1). Next to its associated costs, the training programs also temporarily reduce production capacity, as the trainees cannot fully participate in the production operations during the training program. As a result, the workforce reduction in a kitchen during the training periods has hence to be compensated, *e.g.*, by hiring temporary staff or shifting production activities towards the other kitchen.

Skills	Production activity		
	Preparation (1)	Processing (2)	Packaging (3)
1	X	—	—
2	X	X	—
3	X	X	X

Table 4.1. Skill-activity compatibility matrix

Between the two available nursing home kitchens, one (NH_1 in Figure 4.1) has more modern facilities with a considerably higher capacity. NH_1 can therefore also partially produce meals by performing some of the production activities. The partially produced foods are then sent to NH_2 where production process is completed and the prepared meals are delivered to customers. Such transhipment of partially produced meals is necessary only when NH_2 does not have sufficient capacity to completely cover its customer orders. In order to deal with the expected demand increase, the municipality reserved a budget for the two kitchens to invest in the expansion of the overall production and inventory capacity. Accordingly, different expansion schemes are under consideration, each incurring the municipality a specific cost, while providing kitchens with a certain increase in their production and inventory capacities.

Transportation operations are handled through a homogenous fleet of vehicles owned by an external logistics service provider. The transportation provider charges the kitchens based on the number of required vehicles and the number of destinations to visit. As a result, kitchens are interested in consolidating their shipments to the same customer to decrease the transportation costs. However, their limited production, inventory and labour capacities and the short shelf lives (usually several days) of meals might not allow them to consolidate many shipments. Besides, shipment consolidation might lead to another undesirable result: lower quality meals and possible shelf life violations. The meal delivery network of this municipality is illustrated in Figure 4.1.

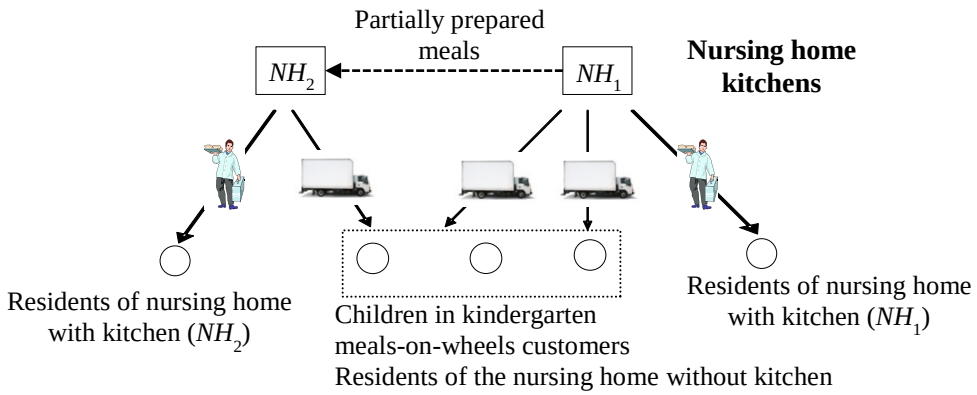


Figure 4.1. Prepared meal delivery network of the case municipality

Summarizing, the planning decisions of this municipal foodservice system are (*i*) the selection among potential capacity expansion schemes, (*ii*) the determination of the required number of permanent and temporary skilled staff, (*iii*) the assignment of customers to kitchens, and (*iv*) the development of daily production and distribution plans. The objective is to minimize the total costs including production and distribution, and labour recruitment and training costs, while serving customers with quality foods. As this plan covers a variety of decisions, both on the design and operational level, a hierarchical modelling framework is developed in the next section to structure, model, and solve the problem.

4.4 Modelling framework

In this section, we present a generic two-level hierarchical modelling approach to formulate a typical foodservice case. Accordingly, we classify decisions as design or operational decisions. On the design level, decisions are more capital-intensive and are made on a more aggregate level using forecasted data for a rather long period of time. In the problem at hand, long-term design decisions include investments in production and inventory capacity. Also, the assignment of customer groups to kitchens, the recruitment of permanent staff, the expected recruitment of temporary staff for specific weeks, and the training of permanent staff are included on the design level. However, the latter decisions can be reconsidered based on the operational plan.

On the operational level, short-term decisions are made for half-day time periods (before and after lunch) based on actual customer orders. These include the assignment of available staff to specific production activities and the detailed planning of production and distribution operations for

the specific time periods. The final allocation of individual persons to production activities within the half-day periods is not included in our models.

4.4.1 Design model

In the more aggregate design model, time buckets, demand and capacity are considered on a weekly level. Customer demand is forecasted on the meal level and then further aggregated to the overall required production time (per activity) based on the capacity consumption of each individual meal. This makes it easier to relate customer demand to its required production capacity, and also reduces the impact of forecasting errors. Also, production capacities of kitchens and productivity coefficients of staff are aggregated to their respective weekly figures. Shelf lives of meals are shorter than one week, and can therefore not be traced through weekly time-buckets. However, by enforcing kitchens to match weekly demand volume with their total production and distribution volume, we avoid long time storage of meals. Finally, the following assumptions were made in modelling the design problem:

- Sufficient raw material is available at kitchens or can be procured based on the production plan.
- Permanent staff is hired at each kitchen for the entire planning horizon, and can neither be laid-off nor re-assigned to other kitchens.
- Temporary staff is hired at each kitchen on a weekly basis if required.
- There is no limitation in hiring skilled workers.
- Certain feasible capacity expansion schemes with known costs are available for each kitchen.
- Expansion schemes are mutually exclusive, i.e. the implementation of one option at a kitchen excludes other options for this specific kitchen. A combination of two independent expansions could be defined as a separate expansion scheme.
- Meals are considered fully produced as soon as their last production activity is performed.
- Transhipment is only defined for the partially produced meals.

The notations and indices used in the design model are as follows:

$w \in W$	weekly time periods
$l \in L$	kitchens
$j \in J$	customer groups
$i \in I$	meals
$m \in PA$	production activities
$PA' \subset PA$	a subset of production activities
$e \in E$	expansion schemes
$s \in S$	skill sets
$s \in S_{PA'}$	skill sets that are compatible with at least one of the activities in set PA'

Parameters:

$c_{m,l}$	unit production cost of running production activity m at kitchen l
$c_{e,l}^{Ext}$	cost of implementing expansion scheme e at kitchen l
c_s^{Perm}	weekly salary of a permanent worker with skill s
c_s^{Temp}	weekly salary of a temporary worker with skill s
$c_{s,s'}^{Train}$	cost of training a worker with skill s to obtain skill s'
c^{Rent}	cost of transportation per vehicle
$ICap_l$	inventory capacity at kitchen l
$ICap'_{e,l}$	extra inventory capacity provided by expansion scheme e at kitchen l
$PCap_{m,l}$	production capacity of activity m at kitchen l
$PCap'_{e,m,l}$	extra production capacity provided by expansion scheme e for activity m at kitchen l
$VCap$	vehicle capacity
α_s	weekly production rate of staff members with skill s
$D_{j,i,w}$	demand forecast of customer group j for meal i in period w
$b_{i,m}$	capacity consumption ratio of meal i from production activity m
$\hat{D}_{j,m,w}$	demand forecast of customer group j for production activity m in period w, calculated by $\hat{D}_{j,m,w} = \sum_{i \in I} b_{i,m} \cdot D_{j,i,w}$.
TB	available total budget for implementing expansion schemes at kitchens

Decision variables:

$\partial_{j,l,w}$	share of customer group j assigned to kitchen l in period w
$Y_{e,l}$	=1 if expansion scheme e is implemented at kitchen l (0, otherwise)
$P_{m,l,w}$	volume of production activity m performed at kitchen l in period w
$Q_{l,w}$	delivery volume from kitchen l in period w

$\bar{Q}_{m,l,l',w}$ transhipment volume from activity m of kitchen l to l' in period w

$\lambda_{l,w}$ number of vehicles needed at kitchen l in period w

$N^{Perm}_{s,l,w}$ available number of permanent staff with skill set s at kitchen l in period w

$\bar{N}^{Perm}_{s,l,w}$ number of permanent staff with skill set s at kitchen l hired at the beginning of period w

$N^{Train}_{s,s',l,w}$ number of permanent staff with skill s being trained to get skill s' at kitchen l in period w

$N^{Temp}_{s,l,w}$ number of temporary staff with skill s hired at kitchen l at the beginning of period w

The objective (4.1) is to minimize the total costs consisting of weekly production, weekly distribution, and staff-related costs. In the considered case municipality, distribution cost should comprise of variable costs based on the number of required vehicles and the number of visited destinations. However, since the design model is solved with weekly time-buckets, the number of visited destinations within a week cannot be determined. Thus, the aggregate distribution cost is calculated based on the number of required vehicles only. The staff-related cost includes the costs associated with hiring permanent and temporary employees as well as the training costs to provide employees with new skills.

$$Min \quad \sum_{w\in W}\sum_{l\in L}\sum_{m\in PA} c_{m,l}\cdot P_{m,l,w} + \sum_{w\in W}\sum_{l\in L} c^{Rent}\cdot \lambda_{l,w} + \sum_{l\in L}\sum_{s\in S}\sum_{w\in W}\left(c^{Perm}_{s}\cdot N^{Perm}_{s,l,w} + c^{Temp}_{s}\cdot N^{Temp}_{s,l,w} + \sum_{s'\in S:s'\neq s} c^{Train}_{s,s'}\cdot N^{Train}_{s,s',l,w}\right) \quad (4.1)$$

Constraints (4.2) ensure that the weekly demand of each customer group is satisfied. $\partial_{j,l,w}$ defines the responsibility of kitchens towards customer groups. It also provides the planner with the possibility of excluding kitchens from serving specific customer groups. For this purpose, the corresponding values of $\partial_{j,l,w}$ can be set to zero.

$$\sum_{l\in L}\partial_{j,l,w} = 1 \qquad j\in J, w\in W \qquad (4.2)$$

Constraints (4.3) match the weekly volume of production activities available at each kitchen with its assigned share of customer groups and the transhipment volume that it receives from and/or sends to the other kitchens. The transhipment variables are set to zero for the last activity ($\bar{Q}_{last(PA),l,l',w}$) in (4.3), as well as in the other constraints, as the concept of transhipment is only defined for the partially produced meals.

$$P_{m,l,w} + \sum_{l' \in L} \bar{Q}_{m,l',l,w} = \sum_{j \in J} \hat{D}_{j,m,w} \cdot \partial_{j,l,w} + \sum_{l' \in L} \bar{Q}_{m,l,l',w} \qquad m \in PA, l \in L, w \in W \qquad (4.3)$$

Constraints (4.4) establish a sequence between production activities. It restricts the total weekly production volume of each activity at each kitchen ($P_{m,l,w} : m$ is not the first activity) on the basis of the available volume of meals processed on the preceding activity in that kitchen and the quantities transhipped to and/or from that kitchen.

$$P_{m,l,w} \le P_{m-1,l,w} + \sum_{l' \in L} \left(\bar{Q}_{m-1,l',l,w} - \bar{Q}_{m-1,l,l',w} \right) \qquad m \in PA, l \in L, w \in W : m \neq first(PA) \qquad (4.4)$$

Constraints (4.5) set the weekly delivery quantity from a kitchen $Q_{l,w}$ equal to its production volume of the last activity ($last(PA)$) making sure that meals are produced and delivered in the same week.

$$Q_{l,w} = P_{last(PA),l,w} \qquad l \in L, w \in W \qquad (4.5)$$

Inventory capacities are considered in (4.6), also including possible expansions. Considering the limited shelf life of meals, it is known that for most of the weeks at least two deliveries per week are required as shelf lives are smaller than a week. However, in order to have a better estimate, the required inventory capacity is defined as a function of the total weekly deliveries and the average shelf lives.

$$\theta \cdot \left(Q_{l,w} + \sum_{l' \in L} \sum_{m \in PA} \bar{Q}_{m,l,l',w} \right) \le ICap_l + \sum_{e \in E} \left(ICap'_{e,l} \cdot Y_{e,l} \right) \qquad l \in L, w \in W \qquad (4.6)$$

In (4.6), θ is a function of average shelf lives weighted on the basis of demanded quantities of products as $\theta = \dfrac{Average\ weighted\ shelf\ life}{Length\ of\ a\ time\ period}$. Small average weighted shelf life leads to less inventory possibility thereby smaller inventory capacity requirement during the week. Also, a larger value of average weighted shelf life means that a big portion of meals can be stored for a longer time resulting in higher inventory capacity requirement.

Constraints (4.7) consider the production capacity, including possible expansions.

$$P_{m,l,w} \le PCap_{m,l} + \sum_{e \in E} \left(PCap'_{e,m,l} \cdot Y_{e,l} \right) \qquad m \in PA, l \in L, w \in W \qquad (4.7)$$

Linking the physical production capacity with workforce availability, expression (4.8) ensures that sufficient number of staff with required skills is available to perform any sub-set of production activities, *e.g.*, PA'. The skill-activity compatibilities are exploited from the corresponding matrix as the one discussed in the problem description section. For a thorough explanation of this modelling technique, we refer interested readers to Grunow *et al.* (2002) and Grunow *et al.* (2004),

where this modelling technique is discussed in detail. Using this modelling technique we can reduce the number of decision variables in the design model, and leave the detailed decision of assigning staff to production activities for the operational model. To determine the required number of staff, a factor (α_s) is considered taking issues like the maximum potential working days of employees into account in calculating their efficient weekly contribution to production activities.

$$\sum_{m \in PA'} P_{m,l,w} \leq \sum_{s \in S_{PA'}} \alpha_s \cdot \left(N_{s,l,w}^{Perm} + N_{s,l,w}^{Temp} \right) \qquad PA' \subseteq PA, l \in L, w \in W \qquad (4.8)$$

Constraints (4.9) balance the number of available permanent staff with a certain skill at a kitchen based on its value in the previous period, the number of permanent staff hired at the beginning of this period, the number of staff who are not available due to attending a training program in this period, and the number of staff who are trained in the previous period ($N_{s',s,l,w-1}^{Train}$ are not defined in the first period).

$$N_{s,l,w}^{Perm} = N_{s,l,w-1}^{Perm} + \bar{N}_{s,l,w}^{Perm} + \sum_{s' \in S: s' \neq s} \left(N_{s',s,l,w-1}^{Train} - N_{s,s',l,w}^{Train} \right) \qquad s \in S, l \in L, w \in W \qquad (4.9)$$

Constraints (4.10) determine the number of vehicles needed to perform the distribution activities in each week.

$$\lambda_{l,w} \geq \frac{\left(Q_{l,w} + \sum_{l' \in L} \sum_{m \in PA} \bar{Q}_{m,l,l',w} \right)}{VCap} \qquad l \in L, w \in W \qquad (4.10)$$

Through (4.11), we ensure that only one expansion scheme can be applied to a kitchen.

$$\sum_{e \in E} Y_{e,l} \leq 1 \qquad l \in L \qquad (4.11)$$

The total expansion cost is restricted to the available total budget (TB) in (4.12).

$$\sum_{l \in L} \sum_{e \in E} c_{e,l}^{Ext} \cdot Y_{e,l} \leq TB \qquad (4.12)$$

Variable domains are defined in (4.13)-(4.16)

$$Y_{e,l} \qquad Binary \qquad (4.13)$$

$$N_{s,l,w}^{Perm}, \bar{N}_{s,l,w}^{Perm}, N_{s,l,w}^{Temp}, N_{s',s,l,w}^{Train}, \lambda_{l,w} \qquad Integer \qquad (4.14)$$

$$Q_{l,w}, P_{m,l,w}, \bar{Q}_{m,l,l',w} \qquad \geq 0 \qquad (4.15)$$

$$0 \leq \partial_{j,l,w} \leq 1 \qquad (4.16)$$

4.4.2 Operational model

In this model, the weekly time-buckets are disaggregated into half-day periods. Meals can only be delivered before lunch time (the first time bucket of each day or the odd periods). As a result, meals produced during the odd periods can be delivered in the same day, and other meals are kept in storage and can be delivered in the following days. The operational model decides on the production and distribution activities for each half-day and the appropriate number of staff to be assigned to these activities. The decisions are made on the basis of actual customer orders and subject to capacity, customer group assignment and the available number of skilled staff decided in the design model.

The operational model focuses on detailed planning and therefore uses more detailed, disaggregated data. It distinguishes between customer orders for individual meals. A minimum food quality level is ensured through tracking shelf lives of meals. Furthermore, the FIFO rule (first-in, first-out) is considered to supplement the shelf life consideration. The FIFO rule makes sure that for the delivery of two different units of a certain meal, the one produced earlier is prioritized. The shelf life consideration links different planning periods through allowing early delivery of the customer orders of the first few days of each week in their previous planning week. In this section, we assume the planning horizon of operational model to be H weeks. In Section 5, we discuss how an appropriate planning horizon for the operational model is connected to the customer order arrival process. Moreover, we adopt a similar menu structure to the case municipality where each meal is provided not more than once in the operational planning horizon. To allow for more frequent provision of meals, the menu can be extended by introducing the repeated meals as new meals.

To assign staff to production activities in the operational model, the staffing decisions of the design model and the following assumptions are taken into account:

- Each week comprises of 7 working days.
- Extra salaries are to be paid for assigning staff to production activities during weekends.
- The operational plan must allow two days off for each staff member.
- Each staff member can be assigned to two different activities during the two half-day periods of a day.
- If assigned to production activities during a day, staff members have to work in both half-day periods.

Indices, parameters and decision variables from the design model that are again used in the operational model have the same definition. Following, the new notation used in the operational planning model is introduced.

$t \in D_w$ half-day time-buckets of week w of the H—week planning horizon

$t \in D_w^{Even}$	even periods of week w
$t \in D_w^{Weekends}$	weekend periods week w
$t \in F_i$	potential time periods for production of meal i
$k \in K_j$	customers belonging to customer group j
$s \in S_m$	skills compatible with production activity m

New parameters:

$c_{i,m,l}^{Part}$	unit production cost of activity m in partial production of meal i at kitchen l
$c_{i,l}^{Full}$	unit full production cost of meal i at kitchen l
c^{Trans}	unit transportation cost based on the number of visited destinations
ε_s	ratio of the weekly salary to be paid as bonus for calling skilled staff on weekends
b_i'	inventory capacity consumption ratio of meal i
O_i	potential time period for ordering meal i
$\beta_{i,m}$	complexity ratio of running production activity m for meal i
$d_{i,k}$	volume of meal i ordered by customer k
r_i	shelf life of meal i based on number of periods
M	a sufficiently large number
$\dot{I}_{i,l,0}, \dot{\bar{I}}_{i,m,l,0}$	initial inventories of fully and partially produced meals

New decision variables:

$\eta_{l,k,t}, \eta_{l,l',t}$	=1 if customer k / kitchen l' receives a delivery from kitchen l in period $t \in F_i \Big\vert \bigcup_{w \in H} D_w^{Even}$ (0, otherwise)
$\dot{P}_{i,l,t}$	production volume of meal i at kitchen l in period t
$\dot{\bar{P}}_{i,m,l,t}$	production volume of meal i partially produced through performing its production activity m at kitchen l in period t

$\dot{Q}_{i,k,l,t}$ delivery volume of meal i to customer k from kitchen l at the end of period $t \in F_i \big| \bigcup_{w \in H} D_w^{Even}$ (0, otherwise)

$\dot{\bar{Q}}_{i,m,l,l',t}$ transhipment volume of meal i, partially produced through performing its production activity m at kitchen l to kitchen l' at the end of period $t \in F_i \big| \bigcup_{w \in H} D_w^{Even}$ (0, otherwise)

$X_{s,m,l,t}$ number of staff with skill s assigned to activity m at kitchen l in period t

$\dot{I}_{i,l,t}$ inventory of meal i at kitchen l at the end of period t

$\dot{\bar{I}}_{i,m,l,t}$ inventory of meal i partially produced through performing its activity m at kitchen l at the end of period t

$\dot{\lambda}_{l,t}$ number of vehicles needed at kitchen l in period $t \in F_i \big| \bigcup_{w \in H} D_w^{Even}$ (0, otherwise)

The objective function (4.17) minimizes the total costs comprising of production, distribution and extra staffing costs. The production component involves the cost of producing meals, both fully and partially. The distribution cost in the operational model consists of renting cost of vehicles and the cost of visiting destinations (customers receiving meals, as well as kitchens receiving partially produced meals). The extra staffing cost represents the extra salaries that must be paid to assign staff to production activities during weekends. The extra salaries are calculated as ratios of the permanent staff salaries $\left(c_s'' \cdot \varepsilon_s\right)$.

$$
\begin{aligned}
Min \quad & \sum_{t \in F_i} \sum_{l \in L} \sum_{i \in I} \left(c_{i,l}^{Full} \cdot \dot{P}_{i,l,t} + \sum_{m \in PA} c_{i,m,l}^{Part} \cdot \dot{\bar{P}}_{i,m,l,t} \right) + \\
& \sum_{t \in F_i \big| \bigcup_{w \in H} D_w^{Even}} \sum_{l \in L} \left(c^{Rent} \cdot \dot{\lambda}_{l,t} + \sum_{k \in \bigcup_{j \in J} K_j} c^{Trans} \cdot \eta_{l,k,t} + \sum_{l' \in L} c^{Trans} \cdot \eta_{l,l',t} \right) + \\
& \sum_{t \in \bigcup_{w \in H} D_w^{Weekends}} \sum_{l \in L} \sum_{m \in PA} \sum_{s \in S} \left(c_s^{Perm} \cdot \varepsilon_s \cdot X_{s,m,l,t} \right) \qquad (4.17)
\end{aligned}
$$

Expression (4.18) ensures that customer orders are fully covered before the shelf lives of meals are expired. $\partial_{j,l,w}$ is provided by the design model to define the responsibility of each kitchen towards customer groups. The shelf life monitoring is performed through defining certain potential delivery periods for each meal (F_i) on the basis of its ordering period $\left(O_i\right)$ and its shelf life duration $\left(r_i\right)$. For this purpose, we define F_i as following:

$$F_i = \left\{ \max\left(1, O_i - r_i\right), ..., O_i \right\}$$

As a result, a meal, *e.g.*, with the shelf life of 5 periods and the potential ordering period of 9, can only be produced between periods [4,9], and can only be delivered in the odd time-periods between [4,9]. This ensures that the time-interval between the start of production activities and the delivery time is less than the shelf life for each meal.

$$\sum_{t\in F_i|D_w^{Even}} \sum_{k\in K_j} \dot{Q}_{i,k,l,t} = \partial_{j,l,w} \cdot \sum_{k\in K_j} d_{i,k} \qquad i\in I,\ j\in J, l\in L, w\in H : O_i \in \{(w-1)\cdot 14+1,\ldots,w\cdot 14\} \quad (4.18)$$

Expression (4.19) ensures that the number of staff that can be assigned to production activities in each period is smaller than the number of hired staff during that week. However, since we have to consider two days off for each employee, we restrict the number of periods that each staff can be called in a week from 14 to 10 through expression (4.20).

$$\sum_{m\in PA} X_{s,m,l,t} \le N_{s,l,w}^{Perm} + N_{s,l,w}^{Temp} \qquad s\in S, l\in L, w\in H, t\in D_w \quad (4.19)$$

$$\sum_{t\in D_w} \sum_{m\in PA} X_{s,m,l,t} \le 10\cdot\left(N_{s,l,w}^{Perm} + N_{s,l,w}^{Temp}\right) \qquad s\in S, l\in L, w\in H \quad (4.20)$$

Expression (4.21) ensures that the total number of assigned staff is the same in the two periods of each day.

$$\sum_{m\in PA} X_{s,m,l,t} = \sum_{m\in PA} X_{s,m,l,t-1} \qquad s\in S, l\in L, t\in \bigcup_{w\in H} D_w^{Even} \quad (4.21)$$

Production volumes are restricted on the basis of staff assignment decisions through (4.22) and on the basis of production capacity through (4.23). In (4.22), $\beta_{i,m}$ is defined to distinguish between the complexities of producing different meals. The production rate of workers at one period of a week is denoted by $\frac{\alpha_s}{10}$. In (4.23), production volumes are bound to be smaller than or equal to the available production capacities obtained via the design model. The production capacity of kitchens in a specific period is denoted by $\frac{PCap_{m,l}}{14}$. As mentioned before, the detailed scheduling of working shifts for individual staff members is beyond the scope of our model.

$$\sum_{i\in I:t\in F_i} \beta_{i,m}\cdot\left(\dot{P}_{i,l,t} + \dot{\bar{P}}_{i,m,l,t}\right) \le \sum_{s\in S_m}\left(\frac{\alpha_s}{10}\cdot X_{s,m,l,t}\right) \qquad m\in PA, l\in L, t\in \bigcup_{w\in H} D_w \quad (4.22)$$

$$\sum_{i\in I:t\in F_i} b_{i,m}\cdot\left(\dot{P}_{i,l,t} + \dot{\bar{P}}_{i,m,l,t}\right) \le \frac{PCap_{m,l}}{14} \qquad m\in PA, l\in L, t\in \bigcup_{w\in H} D_w \quad (4.23)$$

Inventory of partially and fully produced meals are traced separately through (4.24) and (4.25). Since meals are considered fully produced as soon as their last production activity is performed, $\dot{\bar{I}}_{i,m,l,t}$ is not defined for the last production activities ($m \ne last(PA)$). Inventory variables of each meal are only defined for its potential production time periods. This will eliminate the possibility of storing meals beyond their defined shelf lives.

$$\dot{\bar{I}}_{i,m,l,t} = \dot{\bar{I}}_{i,m,l,t-1} + \dot{\bar{P}}_{i,m,l,t} + \sum_{l' \in L} \left(\dot{\bar{Q}}_{i,m,l',l,t} - \dot{\bar{Q}}_{i,m,l,l',t} \right) - \dot{\bar{P}}_{i,m+1,l,t} \qquad i \in I, m \in PA, l \in L, t \in F_i \qquad (4.24)$$

$$\dot{I}_{i,l,t} = \dot{I}_{i,l,t-1} + \dot{P}_{i,l,t} + \dot{\bar{P}}_{i,last(PA),l,t} - \sum_{k \in \bigcup_{j \in J} K_j} \dot{Q}_{i,k,l,t} \qquad i \in I, l \in L, t \in F_i \qquad (4.25)$$

Through (4.26) we make sure that the inventory capacities, determined through the design model, are respected in every period.

$$\sum_{i \in I : t \in F_i} b_i' \cdot \left(\dot{I}_{i,l,t} + \sum_{m \in PA} \dot{\bar{I}}_{i,m,l,t} \right) \le ICap_l \qquad l \in L, t \in \bigcup_{w \in H} D_w \qquad (4.26)$$

Expressions (4.27)-(4.29) help determine the transportation cost. (4.27) and (4.28) calculates the number of destinations visited from each kitchen in a period, and (4.29) determines the number of required vehicles.

$$M \cdot \eta_{l,k,t} \ge \sum_{i \in I} \dot{Q}_{i,k,l,t} \qquad l \in L, k \in \bigcup_{j \in J} K_j, t \in \bigcup_{w \in H} D_w \qquad (4.27)$$

$$M \cdot \eta_{l,l',t} \ge \sum_{m \in PA} \sum_{i \in I} \dot{\bar{Q}}_{i,m,l,l',t} \qquad l \in L, l' \in L, t \in \bigcup_{w \in H} D_w \qquad (4.28)$$

$$\dot{\lambda}_{l,t} \ge \frac{\sum_{i \in I} \left(\sum_{k \in \bigcup_{j \in J} K_j} \dot{Q}_{i,k,l,t} + \sum_{l' \in L} \sum_{m \in PA} \dot{\bar{Q}}_{i,m,l,l',t} \right)}{VCap} \qquad l \in L, t \in \bigcup_{w \in H} D_w \qquad (4.29)$$

Variable domains are introduced through (4.30)-(4.32).

$$\dot{I}_{i,l,t}, \dot{\bar{I}}_{i,m,l,t}, \dot{P}_{i,l,t}, \dot{\bar{P}}_{i,m,l,t}, \dot{Q}_{i,k,l,t}, \dot{\bar{Q}}_{i,m,l,l',t} \qquad \ge 0 \qquad (4.30)$$

$$X_{s,m,l,t}, \dot{\lambda}_{l,t} \qquad Integer \qquad (4.31)$$

$$\eta_{l,k,t}, \eta_{l,l',t} \qquad Binary \qquad (4.32)$$

4.5 Iterative solution procedure

The main motivation for pursuing the hierarchical modelling concept is to split an excessively large-size problem with an enormous number of decision variables with different planning horizons, like the problem at hand, into a series of hierarchically interconnected problems each having a smaller number of decision variables with similar planning horizons (Schneeweiß, 1995). Furthermore, it separates the design decisions from the operational decisions, leading to a planning framework that is closer to how planning is performed in practice.

Although the hierarchal modelling concept significantly reduces complexity of decision-making processes, it faces a crucial challenge as well. Due to the aggregation-disaggregation errors and the inaccuracy of aggregated forecast data, the decisions made on the aggregate level (design decisions) might lead to either a non-optimal or an infeasible solution in the lower planning levels (operational decisions) (Schneeweiß, 1995). Thus, a hierarchical modelling framework is often

accompanied by a case-tailored solution procedure that appropriately connects the different planning levels. Figure 4.2 represents the solution approach that we developed to solve our hierarchical models.

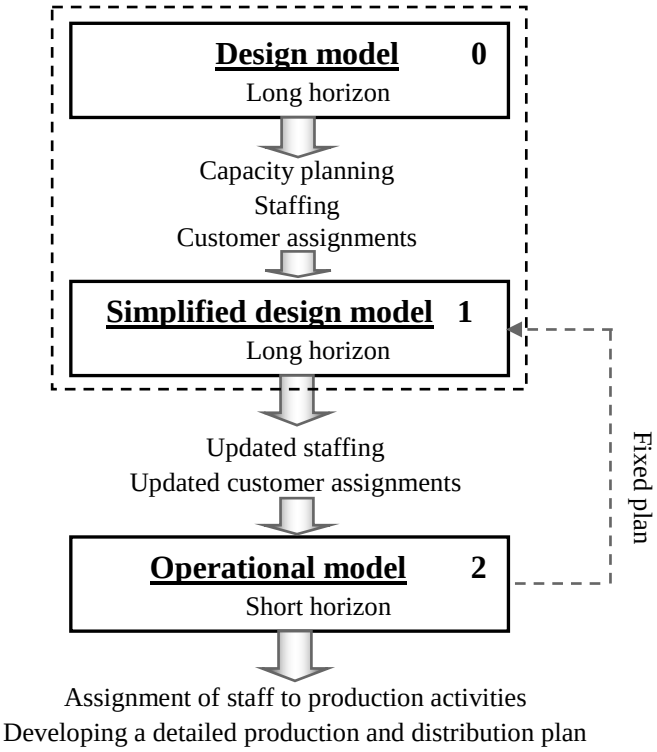


Figure 4.2. Hierarchical modelling approach

To determine the long term capacity plan and the number of staff to be hired, the design model (model (0)) is solved once for a horizon of one year based on the available weekly customer demand forecasts. In practice, model (0) must be solved well in advance to allow for implementation of capacity expansion schemes and also the initial hiring of staff. The capacity related decisions are made for the entire planning horizon and may not be updated. The staffing plan devised by model (0) includes a fixed part and a revisable part. The decisions on hiring permanent workers form the fixed part, and the decisions on hiring temporary workers and training permanent workers are the revisable part of this plan. Moreover, new permanent workers might need to be employed according to the more accurate demand forecasts and the realized customer orders. Also, the assignment of customers to kitchens, which is planned based on the available demand forecasts during the capacity expansion time, needs to be updated if the more accurate demand forecasts are available some weeks before the first planning period. Thus, the staffing and customer assignment decisions are updated by a simplified version of model (0) (model (1)) some weeks before the first planning week according to the more accurate demand forecasts and the realized customer orders. Model (1) is solved for the same planning horizon as model (0) (W weeks) and considers the decisions regarding implementation of expansion schemes ($Y_{s,l}$) as fixed.

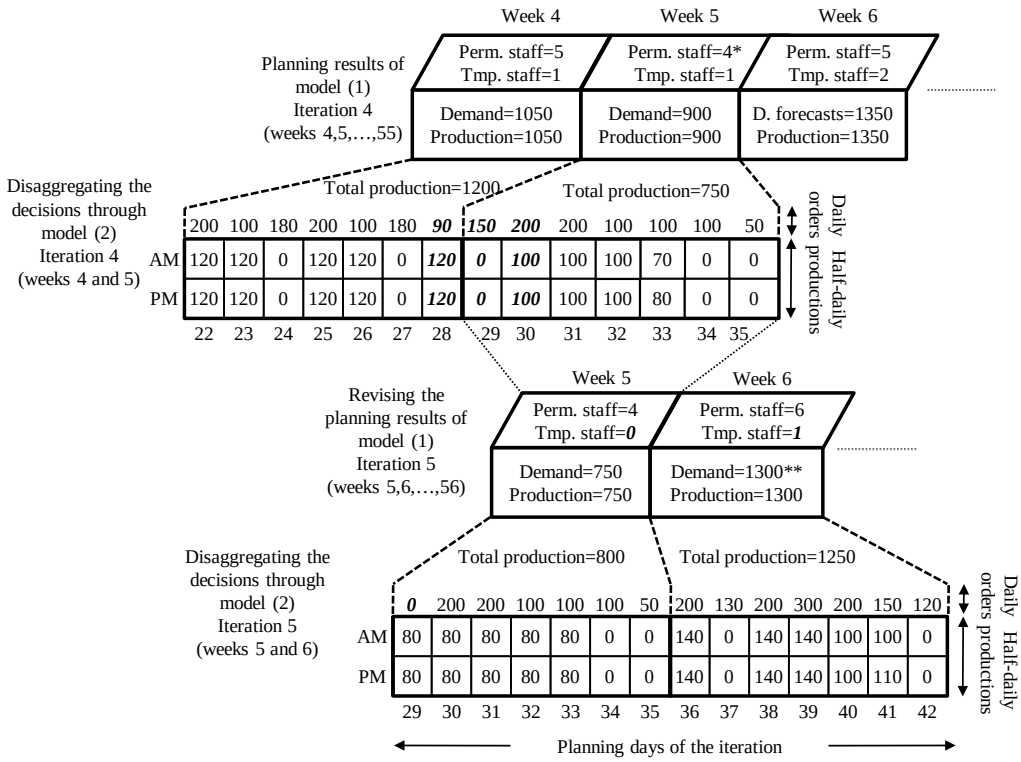
Given the design decisions of models (0) and (1), the operational model (model 2) is solved weekly based on the available customer orders to determine the number of staff to be assigned to production activities during each half-day period, and to develop a detailed production and distribution plan. As opposed to the design models where deliveries are forced to match the weekly demand, the shelf life definition in model (2) allows for consolidation of deliveries between two consecutive weeks when it leads to a lower total costs. To allow for such delivery consolidations, we must run model (2) for a horizon longer than one week. In our case example, customer orders are available for a five-week period. However, the operational model is quite complex due to a large number of binary and integer variables, and also due to its specific structure, *e.g.*, presence of partial production variables and constraints. Thus, despite the availability of customer orders, we solve model (2) in a rolling horizon framework for a horizon shorter than five weeks to reduce the solution time. For this purpose, the length of the time planned at each roll must be determined such that it appropriately links decisions of model (2) to the aggregate decisions made in the design model (1).

Since staffing decisions are made and can be updated on a weekly basis, each run of model (2) should provide one-week of fixed plan. For this purpose, an appropriate customer ordering process must be designed determining the length of time that customer orders must be provided for (the length of planning horizon for model (2)), and the number of days/weeks that customer orders must arrive in advance. As explained before, customer orders must be provided for at least 2 weeks. In practice, a short length of planning horizon might lead to difficulties in planning the recruitment of temporary staff. However, theoretically any planning horizon of longer than two weeks is sufficient. The number of days/weeks that customer orders must arrive in advance depends on the number of weeks for which model (2) must devise a fixed plan at each roll (which is one week in our case municipality). Therefore, in our case municipality, customer orders must arrive at least 7 days (1 week) in advance to guarantee that at the beginning of each week customer orders are available for the entire planning horizon of model (2) (two weeks).

We set the length of a planning roll for model (2) to two weeks in the case municipality. Each roll generates a fixed plan for the first week and an unfixed plan for the second week, which is revised and fixed in the next roll. As explained, the first-week plan might fulfil some customer orders of the second week. Therefore, for running the next roll, the demand of the first planning week should be revised. Consequently, the previously made customer assignment and staffing decisions might not be optimal anymore. Therefore, these decisions are revised in model (1) on a weekly basis. For this purpose, the beginning of the planning horizon of model (1) moves to the next week with each roll of model (2). Also, its demand data are comprised of the actual orders for the upcoming weeks and forecasted data for the rest of the planning horizon. Thus, an iterative solution procedure is established on the basis of the feedback mechanism between the two models that improves the potential sub-optimality of the aggregate decisions.

Illustration of the hierarchical framework

To illustrate how the hierarchical framework acts, Figure 4.3 shows the iterative solution procedure for two planning iterations of a small case study. The main aim of Figure 4.3 is to illustrate the detailed planning and modification of aggregate production and staffing decisions according to demand updates. Thus, a simple problem structure with only one kitchen, one customer, one product, one skill and one production activity is considered and the distribution decisions are not visualized to avoid a too complex figure. As displayed in this figure, in model (1), the weekly production quantities match the demand. This is re-planned in a more detailed level in model (2) to benefit from the consolidation possibilities. For instance, in the last day of week 4 (day 28), the production quantity resulting from model (2) is 240 units while the demand for this day is only 90. The extra 150 units of products are produced to cover the demand of day 29 (in week 5). Thus, the demand of day 29 is revised in iteration 5 by deducing the 150 units that were produced in the previous period. Revising model (1) with the updated demand for week 5 changes the previously made decision of hiring one temporary staff for this week. Therefore, within a week, consolidation of production tasks allows better usage of staff and production resources, and between two consecutive weeks (as between weeks 4 and 5 in this example), it results in changing the total weekly demand and correspondingly different production and staff requirement.



*One permanent staff is being trained during week 5.
**At the beginning of week 5, customer orders of the next five weeks arrive and replace the demand forecasts in model (1).

- For the sake of simplicity, only one kitchen, one customer, one product, one skill, and one production activity is considered.
- Weekly production rate of staff is 200 (daily production rate of staff is 40), and all products have the same shelf-life of three days.
- AM represents the odd time periods and PM represents the even time periods.
- Numbers presented in bold-italic are referred to in the text.

Figure 4.3. Illustration of disaggregation and revision of the aggregate plan (mode 1) into a detailed plan (model 2)

Moreover, at the beginning of week 5, the demand data in model (1) is updated by replacing the demand forecasts, e.g., for week 6, with the newly arrived orders. Accordingly, the previous plan made by model (1) is revised by taking into the account the actual customer orders. In the illustrated example, this leads to one unit reduction in the number of necessary temporary staff for week 6.

This example illustrates how the sub-optimality of the aggregate decisions can be improved based on the updated demand data. To some extent, this method can also handle potential infeasibilities of some of the aggregate decisions, which will be further discussed in the following section.

Handling infeasible aggregate decisions

The operational model might face infeasibility due to aggregation-disaggregation errors of the decisions made by model (1). For instance, due to demand variations between different days of a week and the limited shelf lives of meals, the customer assignment or staff capacities decided by model (1) might not be appropriate to cover customer orders of each individual day. In such cases, we first try to solve the infeasibility by revising the customer assignments, as it might not impose any extra cost to the system. If this cannot remove the infeasibility, we must hire new temporary workers to increase the staff capacity. Nevertheless, we cannot cover all customer orders when the source of infeasibility is the lack of physical production or inventory capacities during our W-week planning horizon. Here, the detailed procedure of handling infeasibility is explained.

(i). To revise the customer assignments, we take the following procedure:

- Relax the customer assignment decisions ($\partial_{j,l,w}$) made through (1), and consider them as decision variables in model (2).
- Add constraints (2) to model (2).
- Run model (2).

(ii). If the above procedure fails to remove the infeasibility, we must hire new temporary workers to cover the demand peaks in infeasible week(s). This can be performed as following:

- Introduce new decision variables to decide on the number of necessary temporary workers ($\dot{N}^{NewTemp}_{s,l,w}$).
- Revise constraints (4.19) and (4.20) by replacing $N^{Temp}_{s,l,w}$ with $N^{Temp}_{s,l,w} + \dot{N}^{NewTemp}_{s,l,w}$.
- Revise the objective function (4.17) to account for the newly employed temporary staff as following:

$$
\begin{aligned}
Min \quad & \sum_{t\in F_i}\sum_{l\in L}\sum_{i\in I}\left(c^{Full}_{i,l}\cdot \dot{P}_{i,l,t} + \sum_{m\in PA} c^{Part}_{i,m,l}\cdot \dot{\bar{P}}_{i,m,l,t} \right) + \\
& \sum_{t\in F_i \mid \bigcup_{w\in H} D_w^{Even}} \sum_{l\in L}\left(c^{Rent}\cdot \dot{\lambda}_{l,t} + \sum_{k\in \bigcup_{j\in J} K_j} c^{Trans}\cdot \eta_{l,k,t} + \sum_{l'\in L} c^{Trans}\cdot \eta_{l,l',t} \right) + \\
& \sum_{w\in H}\sum_{l\in L}\sum_{s\in S}\left(c_s^{Temp}\cdot \dot{N}^{NewTemp}_{s,l,w} \right) + \\
& \sum_{t\in \bigcup_{w\in H} D_w^{Weekends}} \sum_{l\in L}\sum_{m\in PA}\sum_{s\in S}\left(c_s^{Perm}\cdot \varepsilon_s \cdot X_{s,m,l,t} \right)
\end{aligned}
\tag{4.33}
$$

- Run model (2).

4.6 Numerical results

To obtain a better insight into the problem, we investigate different planning scenarios for the case municipality. Here, the information provided through the problem description section is extended by presenting a detailed description of several data elements used in the numerical tests. Some changes and assumptions were however made to obtain a setting that illustrates the core aspects of the problem at hand. For instance, some of the customer assignments were predetermined in the case municipality, which were relaxed in the model to illustrate the model's capabilities. Here, an important consideration was the potential use of the model in similar decision problems.

The composition of customer groups and their ordering profile is as follows.

- Customer group 1 comprises 269 residents of nursing homes with kitchens (NH_1, NH_2) served with hot meals inside their nursing homes on a daily basis.
- Customer group 2 includes 72 residents of the nursing home without kitchen.
- Customer group 3 comprises 100 elderly receiving foods in a meals-on-wheels framework.
- Customer group 4 represents 6 kindergartens each ordering 46 meals per day.
- Customer groups 2, 3, and 4 can be served by each of the two kitchens.
- For each day, customer groups 2, 3, and 4 can select between 2 different available meals from the menu. Therefore, a total number of 28 meals are produced at kitchens during a period of two weeks.
- Customers provide their meal selections for a 5-week period 10 days in advance.

To better represent the real case, different probabilities are considered on whether a customer orders for a certain day, and which product he orders. Accordingly, the peak demand days are placed on Wednesday-Friday and the weekends represent the lowest potential demand days. Weekly salaries of staff depend on their skill level and their employment type. Hiring cost depends on staff skills. Besides, hiring temporary staff is more costly than hiring permanent staff. Similarly, staff training costs depend on the destination skill and is higher for more advanced skills (skill 3 > skill 2 > skill 1). Different weekly production rates are considered for the staff on the basis of their

skill levels. Production unit costs are set the same for all products and are more expensive in kitchen 2, as it does not have the same advanced equipment of kitchen 1. Further, partial production unit costs are set such that producing meals through breaking different tasks between kitchens becomes more costly than full production of meals in the same kitchen. This is due to extra costs of packaging the partially produced meals. In the transportation cost parameters, the vehicle renting cost is set twelve times as big as the visiting cost of each customer. This ratio is decided in relation to other cost parameters and reflects the trade-off between the preference over reducing the number of visited customers per transportation versus reducing the number of required vehicles.

Some initial inventories are assumed to be available to cover some orders in the first planning period. Also, to distinguish between different meals, capacity consumption ratios of meals for production activities are defined as random numbers that are uniformly distributed between 0.6 and 1.4. Production and inventory capacities of kitchens are set according to the information obtained from the case municipality. To extend the available capacities, four different expansion schemes were identified each providing kitchens with certain extra production and inventory capacity. Table 4.2 summarizes the percentage of extra capacities provided through each expansion scheme and its corresponding cost. Due to an investment budget limitation of 4 million DKK and according to the cost of expansion schemes, only some of the potential schemes can be selected. Moreover, only one expansion scheme might be applied to each kitchen.

	Extra production capacity						Extra Inventory capacity		
	Production activities of NH1			Production activities of NH2					
Scheme	1	2	3	1	2	3	NH1	NH2	Cost (DKK)
1	51	52.8	10.4	51	53	32.4	35.2	69.2	1,500,000
2	55.2	56.7	15.6	46.5	39.7	48.6	52.9	23	2,500,000
3	63.1	64.8	31.3	51.7	52.9	56.7	70.5	23	3,000,000
4	31.5	32.4	9.4	41.3	44.1	24.3	17.6	46.1	1,000,000

Table 4.2. Potential expansion schemes

Both design models ((0) and (1)) and the operational model (2) are implemented in IBM ILOG OPL 6.1.1 as the modelling tool and CPLEX 11.2 as the solver. All calculations are performed on a PC with Intel P4 2GHz CPU and 2GB RAM. In terms of computational time, the solution to each run of the design and operational models can be obtained within acceptable duality gaps of 1.5% and 1.1% in less than 10 seconds and 10 minutes respectively. The iterative algorithm frequently faced infeasibilities among which only a few occasions could successfully be treated by rearranging customer assignments. In the other cases, the infeasibility is treated through hiring new temporary staff. In the resulting solution of our integrated approach, the design model (model (0)) selected expansion scheme 3 to extend the capacities at kitchen 1, and scheme 4 to increase the capacities at kitchen 2. As the municipality expects certain annual investment in its meal delivery system, this decision is made based on the demand forecast of the first year by model (0) and will not change for the entire year.

A key characteristic of the solution algorithm is the weekly revision of the decisions made by model (1) based on the operational plan developed by model (2). To show the effect of these

revisions, we compare the results of solving the case problem for a short horizon of seven weeks with and without the feedback mechanism. As displayed in Table 4.3, the feedback mechanism results in 0.23% less total costs even in such a short planning horizon. The realized cost saving is partly reflected in the less expensive staffing plan, and partly in the production and distribution related costs. The realized cost saving is due to consolidation of production and distribution operations especially for the last days of the week to cover some of the customer orders of the first few days of the next week. Thus, the remaining demand of the next planning week is often different from the initial demand consideration in model (1). In our case study, updating the demand information upon the result of model (2) and re-running model (1) leads to considerable amount of cost savings.

	Total costs	No. of permanent staff (in work days)			No. of temporary staff (in work days)		
		S1	S2	S3	S1	S2	S3
Without the feedback mechanism	18107569.3	445	430	535	0	60	20
With the feedback mechanism	18066147.5	435	415	545	20	30	35

The number of staff is calculated by multiplying the number of staff during each week with five work days per week

Table 4.3. The effect of the feedback mechanism on the results of a seven-week plan

As an important contribution of this study, Table 4.4 illustrates the impact of workforce integration as percentage of changes in several key planning measures for the case municipality compared to the results of a non-integrated planning methodology. The results for the non-integrated planning are obtained through first finding the optimal production and distribution plan assuming sufficient workforce is available to fulfil such plan. Then, the production and distribution related variables are fixed as constraints in determining the number of necessary employees. However, in our planning model upper limits, based on staff experiences, are considered for the number of temporary staff that can to be hired each week to avoid a too uneven distribution of workload among different planning days.

Total costs	No. of permanent staff			No. of temporary staff			Transhipment volumes
	S1	S2	S3	S1	S2	S3	
-4.6	18.1	0	0	-91.9	-80.6	-77.9	271.7

Table 4.4. Percentage of change in some of the key planning measures due to the integration effect

After implementation of the expansion schemes, the daily production and inventory capacities of kitchens are noticeably higher than the current daily demand. Thus, availability of the skilled employees becomes the major capacity factor. However, the non-integrated planning procedure only takes the physical production capacities and an upper limit on the potentially available employees into account for planning the production and distribution operations. Thus, its optimal production and distribution plan consolidates the production and distribution operations much more compared to our integrated approach. Such approach leads to hiring a large number of employees,

especially temporary employees that are hired by the operational model. Moreover, the total transhipment volumes can be significantly low, due to neglecting staff-related constraints, simplifying the production operations compared to our integrated model. However, it might not always be that easy to find temporary workers in practice. As an important benefit of integrating the workforce plan with the production and distribution plan, the integrated approach results in hiring a remarkably lower number of temporary staff in the entire planning horizon. Besides, the integrated method resulted in about 4.6% reduction in the total costs which is a significant change taking into account that the value of the total costs is quite large. Furthermore, such total costs reduction is considerably important in the foodservice sector where the profit margin is usually very low.

Since partial production activities complicate the production operations, the kitchens prefer to eliminate or reduce them by as much as possible. The amount of partial production activities is directly linked to the total transhipment volumes and is affected by the following factors: production and inventory capacities, cost parameters, shelf lives of meals and staff profile at kitchens. Among these factors, the total production and inventory capacity depends on the total available budget and cannot be expanded beyond a certain limit. Thus, we analyse revisions of our integrated model in its cost parameters, shelf lives, and available staff profiles with the aim of further reducing the amounts of transhipments. Figure 4.4 illustrates the analysis of cost parameters and shelf life extension in changing the key planning measures (the results are normalized based on the corresponding figures of the non-integrated models to represent a comparison between the current way of working and the applied integrated models). In the penalized transhipment model, we considered a rather high penalty cost for performing any transhipment operations. The added cost term is however not included in calculating the total costs and is only added to reduce the desirability of solutions with transhipment in our integrated model. This strategy reduces the transhipment operations for about 13.1% compared to the results of integrated model without a transhipment penalty cost. Next to the fact that such reduction in transhipment operations simplifies the production operations at kitchens, it is also commercially viable (compared to the non-integrated model) as it only increases the total costs for about 1.4%. To analyse the effect of shelf life, we extended the possibility of storing meals for one extra day in our integrated model. As illustrated in Figure 4.4, this consideration resulted in even better results than the other models by reducing the transhipment volumes by 22.9% and the total costs by 0.3%. Therefore, if the municipality spends more money on procuring higher-quality ingredients to extend the shelf life of meals, it can reduce the total operational costs and obtain smaller amounts of transhipments and potentially higher quality meals.

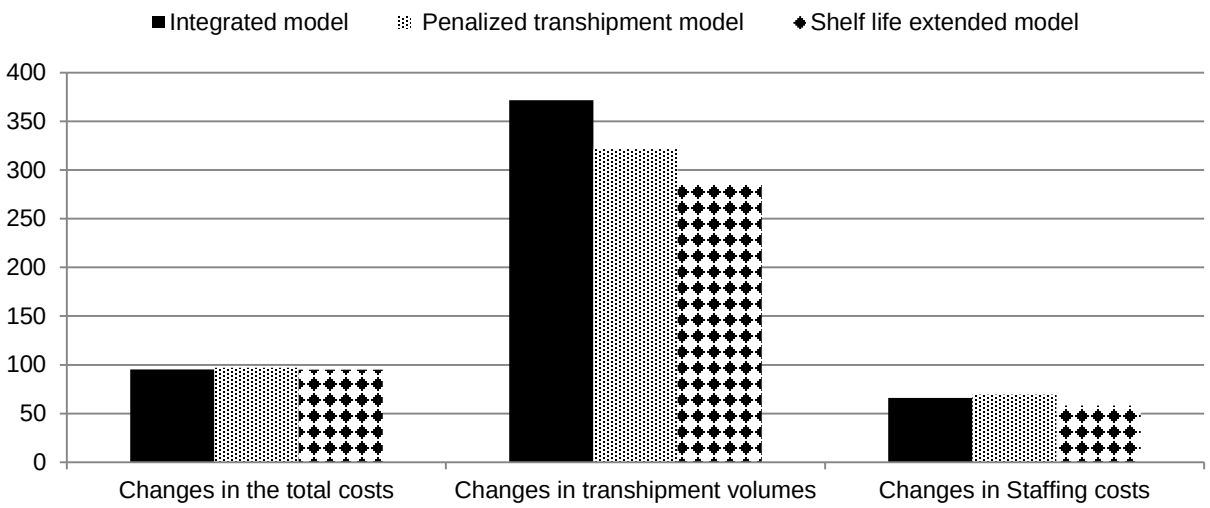


Figure 4.4. Partial productions vs. the total costs

The range of required workforce skills complicates the planning tasks in the foodservice sector. Furthermore, the available staff profile at kitchens also influences the total transhipment volumes. Here, we investigate this issue through running the integrated model combined with three different staff profiles at kitchens: staff with only dedicated skills, staff with flexible skills, and staff with fixed assignment to production activities during a week. In the dedicated skills setting, we assume that each skill only perform one activity, and for the flexible skills setting we define one flexible skill (skill 3) which is capable of covering all activities. As illustrated in Figure 4.5, adding the flexible skill assumption to our integrated model reduces the transhipment volumes by 37%. However, the total costs increase with 3.8%. Compared to the dedicated skills settings, the flexible skills setting results in a 36.5% lower transhipment volume, which means hiring staff with dedicated skills does not strongly contribute in reducing transhipment volumes. Regarding the change in staffing cost and the total costs between the flexible and dedicated settings, even though the flexible skills setting results in hiring a smaller number of staff, it increases the total staffing costs by 39.9% (due to a higher hiring cost) and the total costs by 2.8%. However, this strongly depends on the difference between the hiring costs for difference skills. To investigate this dependency, we also studied a situation in which the hiring cost of different skills differed less than in our initial case. Despite the higher staffing costs, the total costs of the flexible skills setting were smaller than the dedicated skills setting due to a decrease in the total production and distribution costs. In such cases, the municipality should invest in hiring more expensive staff which leads to higher potentials in reducing the production and distribution costs. Furthermore, Figure 4.5 also presents the result of analysing the case municipality subject to fixing the assignment of staff to production activities during a week in our model. This is a practical consideration as in reality staff often have a limited set of responsibilities by being in charge of operations at a certain part of the kitchen. We defined this scenario by introducing a new constraint set on the number of skilled staff assigned to activities during each period of a week (analysing the individual assignment of staff to production activities is not within the scope of our work) as follows:

$$X_{s,m,l,t} = X_{s,m,l,t+1} \qquad s \in S, m \in PA, l \in L, w \in H, t \in D_w : t \neq last(D_w) \qquad (4.34)$$

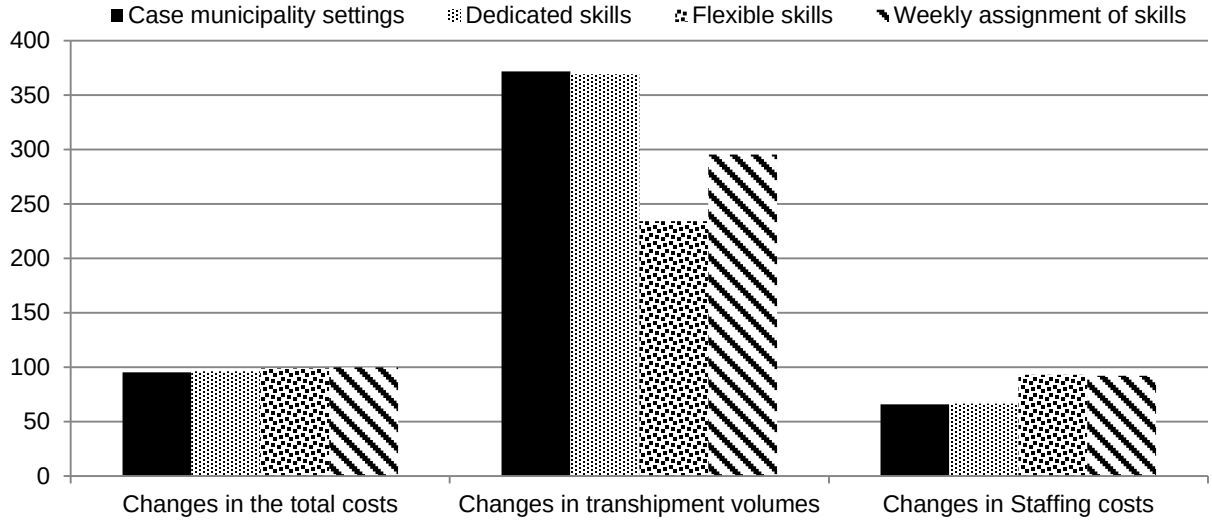


Figure 4.5. The importance of defining skill settings

The last bars in Figure 4.5 show that weekly assignment of skills to production activities in the case municipality results in higher staffing costs compared to our case municipality settings due to higher number of employed staff (39.7%). Further, the lack of flexibility in moving staff between different activities increases the total costs (comprising of production, distribution and staffing costs) to the highest level among the developed settings (4.8% more expensive than the initial case settings). The results also show the potential benefits of this consideration in terms of reducing transhipment volumes compared to the current setting of the case municipality (20.5%), even though it only reaches about half of the benefits of a fully flexible staff. Summing up the results, implementation of this scenario might only be necessary when the required skills for running production activities are very difficult to obtain, or when the kitchens are so large that one employee cannot cover different activities in different parts of the kitchens.

4.7 Conclusions and future research directions

In this paper, the planning of workforce, production, and distribution are discussed in the foodservice sector, and the necessity of taking an integrative approach towards these problems is explained. The proposed integrated hierarchical planning approach decomposes the decision problem into design aspects and operational aspects which are presented in generic mathematical models. The models represent the major challenges in the foodservice sector focusing on integrating workforce planning with other planning decisions. Also, an iterative solution procedure is devised taking into account the process of customer orders arrival. Capturing the interdependencies between different decision levels, the solution procedure connects and solves the developed models. It also improves the sub-optimality and handles the potential infeasibilities, which are the natural results of aggregation-disaggregation errors in hierarchical planning methodologies. To analyse the effect of our approach on the total costs, the complexity of production operations and the staffing decisions, numerical studies are performed based on a real case in a municipality of Denmark. Next to illustrating the application of the proposed models, the numerical analysis of the case study suggests

that taking an integrated approach leads to a significant improvement in some key planning measures, e.g., the total costs and the number of required staff. Furthermore, the effects of combining different policies like extending shelf lives, penalizing transhipments and different staffing strategies with our integrated approach are analysed. By applying an appropriate integrated planning approach focusing on the reduction of production, distribution, and workforce costs, a larger part of the budget of the municipality could be used in the procurement of high-quality ingredients, improving the quality of the meals provided to the elderly and young.

The proposed modelling approach appropriately determines the number of necessary staff to be assigned to each production activity in coordination with the capacity, production and distribution plans, and establishes a proper ground for the more detailed scheduling of staff based on their preferences and their availability times. The potential benefits of further integrating our operational model with the staff scheduling problem still need to be investigated. We believe the selected case municipality appropriately resembles a generic case. Also, the result of our numerical analysis proposes different decision policies like extending shelf life, or hiring flexible staff to improve the total costs and/or transhipment volumes. These recommendations can be further supported through designing appropriate experiments on correlations between the proposed policies.

Chapter 5. Conclusions and future research directions

In this dissertation, we focus on discussing and developing advanced planning methodologies to optimize operations in food supply chains. A Supply chain 'is a network of organizations that are involved, through upstream and downstream linkages in the different processes and activities that produce value in the form of products and services in the hand of the ultimate consumer' (Christopher, 1998). According to this definition, food supply chains comprise of the following components: agriculture and farming industries, the food processing industry, the distribution industry, and final consumers. This thesis mainly focuses on the part of the supply chain which starts from the food processing industry.

This concluding chapter summarizes the conclusions which are drawn in the research discussed in the previous chapters and outlines some directions for future research. To do this, we address each of the three research questions that we raised in the introduction chapter one by one and present the main conclusions and managerial insights of the research studies conducted in this thesis.

RQ1 How are the main challenges of operations planning in food supply chains covered in operations management literature and what are the potential relevant extensions?

In chapter 2, we classify the food distribution operations management literature through a hierarchical framework into three levels of distribution network design, distribution network planning and transportation planning. Within each of these levels, we survey the research contributions, discuss the state of the art and identify challenges for further research. Furthermore, we also review articles that take an integrative planning approach including two or more planning levels. Special focus is given to the main challenges in the food industry including food quality, safety and sustainability. In the following, our conclusions are summarized for the different planning problems.

The results of our survey indicate that the number of contributions on food distribution network design is relatively low. Further, missing the main food characteristics, most of the related literature are actually rather generic facility location-allocation studies; i.e., there are no aspects that make the studies distinctive for the food industry. The inclusion of product quality was seen in some recent work, but still seems to be in its infancy. Food quality is considered either as a penalty function on the total quality degradation in the objective function, or as a constraint where it is used to limit the total quality degradation in the distribution network. Food safety considerations are thus far not addressed in network design research, and sustainability is explicitly only included through relating the travelling distance in networks to its environmental impact.

On the network planning level, there are also some studies that explicitly model quality change of food products throughout production and distribution networks and some others that deal with the issue implicitly through defining shelf-life related constraints. Most of the modelling approaches on this level are developed with time discretization in months (as is typical in aggregate flow models), which make them only applicable if the quality decay of the food is limited. If highly perishable food is regarded, the time discretization needs to be more detailed to be able to include this in the model, which usually leads to computational problems, and suitable aggregation schemes need to be developed. Detailed analysis of the trade-off between quality degradation and storage, handling or transportation costs is still quite limited on this level. As an alternative approach, simulation studies are developed by some authors to evaluate food quality next to the cost aspects. Food safety has also seen only limited (and recent) consideration in terms of reducing the impact of possible recalls by limiting the dispersion of production batches in distribution networks. Sustainability is only considered in a limited way through defining cost elements that also have an environmental side, such as the temperature control factors. These factors relate to energy use for refrigeration, an important aspect in the discussions around the environmental impact of food transportation.

In transportation planning, quality aspects have mostly been considered implicitly by assuming that the planning horizon is shorter than the shelf life of the products or by minimizing transportation time and distance. Some explicit approaches towards modelling food quality during transportation do however exist. They mainly model quality degradation as a (continuous) decrease in product value, usually neglecting the fact that products are considered completely perished at a certain quality level. Looking into the literature, we could not find any contribution explicitly improving food safety in transportation planning. Several approaches try to utilize driver knowledge by assigning certain groups of customers to the same driver. Indirectly, this is a way to increase food safety, as the driver's knowledge would also include information of food control systems used by the customer (including, e.g., temperature checks and sampling for quality control). Sustainability measures are explicitly included in the transportation planning problems by trying to reduce the energy consumption, including the reverse flow of, e.g., empty bowls and plates in the foodservice industry. Including these flows in modelling approaches can be very useful in relation to sustainability and could, for instance, be used to evaluate the impact of using recyclable packaging material.

Finally, our review of integrated approaches towards food distribution management reveals only a limited attention to food quality and none to food safety and sustainability. Modelling degradation throughout the network through improving coordination between production and transportation planning allowing for better quality control would be of significant benefit.

In general, it has to be noted that most of the literature on food distribution management does not cover the key challenges found in the food industry. Most noticeable in the review is that there are very few studies in the literature that include food safety aspects in distribution management. The importance of product quality is, however, reflected to a slightly larger extent in the current research, both in the number of contributions and in the variety of the methodology used. Most of the contributions reviewed in this paper do not specify the temperature level during distribution,

even though temperature control is a main factor with regard to the control of food quality and food safety. Despite the fact that today's society is more and more concerned with sustainability, this review shows that there is only very limited attention to designing and operating sustainable food distribution networks. In the few cases in which sustainability is considered, it mainly concerns the environmental dimension of sustainability. The lack of attention to the social dimension is likely due to the fact that it is harder to quantify.

Finally, it is worth mentioning that most of the research so far is aimed at the retail industry, whereas the foodservice industry received much less attention. This is probably highly related to the prevalence of SMEs in this sector, where the development and use of the kind of decision support models described in this paper is less common than in the larger companies found in the retail industry.

RQ2 What are the potential impacts of coordinating production and distribution operations on the total operations costs and the quality of delivered products in the foodservice sector?

The third chapter of this thesis is dedicated to investigating quality improvement in a foodservice company by coordinating production and distribution operations. Through explaining typical production and distribution operations in the foodservice sector and developing generic mathematical models, we show the complexity of this problem and the need for developing appropriate modelling and solution technique. The proposed block-planning-based MILP model and decomposition procedure significantly improve tractability of the model and allow analysis of different planning scenarios. The presented numerical results suggest that taking an integrative approach towards production and distribution operations can significantly improve the quality of meals without drastically increasing the total costs. Further, we discussed a measure of fairness to guarantee an appropriate quality level among all customers. The results of our analysis also explicitly show that the stronger the link between food quality and storage time (higher perishability factor), the larger the achievable improvement through integration of production and distribution operations. Finally, as improving the quality increases the total costs, an appropriate trade-off has to be made between the quality-related component and cost-related terms in the objective function. We suggest a scenario analysis method to set the appropriate weight parameter for the quality related component beyond which emphasizing on quality improvement might not worth the corresponding increase in the total costs.

RQ3 What are the potential benefits of integrating workforce planning with production and distribution operations in the foodservice sector?

We addressed this research question in Chapter 4 by analysing the design and operations planning for a municipal meal delivery system. Implementing the developed models and the solution algorithm for the case study and comparing the results with a non-integrated approach suggests a noticeable reduction in the number of temporary staff hired, and in the corresponding staffing cost, also leading to a reduction in the total costs. The result of the numerical analysis also implies that investing in higher quality ingredients, which can increase shelf lives of meals, is an appropriate strategy that combined with our integrated method provides planners with the possibility to better optimize their production and distribution operations, and consequently reduce the total costs. Combining other strategies like penalizing transhipments in the model, hiring flexible versus dedicated staff and fixing the assignment of skilled staff to production activities on a weekly level are also tested, and their results are analyzed for the case municipality. Next to the managerial insights obtained from each individual research projects, the whole thesis suggests that in order to obtain better results from using advanced planning methodologies, specific characteristics of the foodservice sector has to be taken into account. Also, results of chapters 3 and 4 imply that due to the strong interdependency of planning tasks in the foodservice sector, significant improvements can be achieved in the selected planning measures by integrating different planning tasks, which has not been researched well in the foodservice sector.

Future research:

In this section we present some ideas for future research based on the results of the previous chapters. Looking into the literature, only a few studies take an integrated approach towards operations planning in the food industry. In this thesis, two integrated planning approaches are analyzed with a focus on meals quality in two different foodservice cases. As discussed in chapter 3 and 4, consideration of food related aspects like quality degradation in such planning approaches leads to very complex and often intractable models. One potential way of dealing with the computational burden and the model complexity is to develop hierarchical models based on suitable aggregation-disaggregation schemes. However, more research needs to be done on developing appropriate modelling approaches and solution algorithms.

The results of Chapter 3 confirm that modelling degradation throughout the network through improving coordination of production and distribution operations would be of significant benefit. This is an area that deserves further research, especially for highly perishable food products. We analyzed this problem for a single foodservice company. Our analysis can be further extended by considering a more complex network involving different production sites. Also, we only focus on one production stage as the bottleneck in Chapter 3. A more generic problem might consist of more

than just one bottleneck production stage leading to different appropriate modelling and solution techniques.

Further extension of our studies can also be done by a more detailed analysis of integrating the workforce scheduling with the production and distribution planning. In Chapter 4, we investigate the potential benefits of integrating workforce hiring and training decisions with the production and distribution plan. Future research can extend this by developing an appropriate framework to investigate the effect of such integration on the detailed staff scheduling problem. Also, several potential strategies are discussed in the numerical analysis. The interaction between these strategies, e.g., extending shelf lives and hiring dedicated staff, might result in important managerial insights. Thus, appropriate design of experiments needs to be performed to analyze the potential correlations between these strategies, also in different case studies.

Optimization of safety and sustainability measures were not within the scope of our case analyses. However, the results of our survey indicate a great research potential for improving these performance measures in food supply chain planning. Given the large financial impact on food manufacturers and the risk of exposing often a large number of consumers to serious health dangers, taking active strategies towards food safety risks is vital. To do this, appropriate measures of safety have to be defined, safety risk has to be quantified along the entire supply chain, and its optimization must be integrated with the planning of other supply chain operations. Appropriate strategies towards food safety should minimize the potential threat of safety risks in terms of both its health impact on consumers and its financial impact on the manufacturers in the time of a safety crisis. On the distribution network design level, for instance, planning decisions affect how many actors are involved, how far products travel and how wide they get spread geographically. These factors have a major effect on food safety and on the sizes of potential product recalls. Also, in the transportation planning, the development of methods that use or improve the traceability of foods in the chain could be one way to improve the safety of foods. This could be based on, e.g., some recent approaches that look at the dispersion of raw material or production batches in production and distribution systems. So far, this concept has not been used in relation to transportation planning, but it seems logical to also use this in these decision problems. As such approaches rely on extensive product information; they should be supported by tracking and tracing models, which have been increasingly implemented. Considering the importance of food safety, there are great opportunities for further work in including safety measures in strategic, tactical and operational planning problems.

Regarding sustainability, a new paradigm is expected to appear in the future research on food supply chains. So far, sustainability has mainly been associated with the transportation and particularly the travelling distance focusing on reducing the fuel consumption to lower the environmental pollution. We expect the new chain perspective to focus on integrating sustainability with the other supply chain planning problems, such as production planning. To do this, models must be developed which include reverse logistics and recycling operations in production and distribution decisions to improve the possibilities of a proactive approach to sustainability: e.g. by deciding on plant locations, and when and where to use certain, transport or package options to

minimize the total environmental impact of supply chain operations, something which is currently lacking in the quantitative operations management literature.

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Summary

The Food industry is an important sector both because of its direct impacts on the daily lives and also its large share of GDP among other economic sectors. Thus, this industry is under a severe scrutiny in many societies. In this dissertation, we focus on discussing and developing advanced planning methodologies to optimize operations in food supply chains. Food supply chains comprise of the following components: agriculture and farming industries, the food processing industry, the distribution industry, and final consumers. This thesis mainly focuses on the part of the supply chain which starts from the food processing industry.

Planning tasks in the food industry are associated with certain challenges; with safety, quality and sustainability being the most well-known ones. In the second chapter of this thesis, a thorough review is presented classifying the related contributions in design, tactical, and operational studies, and also integrated studies spanning different planning hierarchies. With this review, we aim at explaining how the key food distribution planning challenges have been dealt with in the Operations Management literature. The result of our review indicates that most of the reviewed articles do not take the key challenges of food industry into account. Particularly, there are very few studies considering safety improvement in food production and distribution operations. Food safety generally refers to the prevention of illnesses resulting from the consumption of contaminated food. In the food industry, safety can be a competitive factor, and more importantly, the implications of food safety failures can be commercially devastating. This includes product recalls, damage to reputation and punitive liability damages. According to the review presented in chapter 2, food safety has only been considered in a quite limited way in the distribution network planning literature through taking safety measures into account for planning dispersion of raw material or production batches.

Sustainability commonly refers to how the needs of the present human generation can be met without compromising the ability of future generations to meet their needs. In our review, current approaches towards sustainability mostly try to reduce energy/fuel consumption as one environmental aspect of sustainability. This is done especially in transportation planning through explicitly connecting the travelling distance to its environmental impact, or by implicitly influencing the sustainability measures through, *e.g.*, deciding on the temperature control factors related to the energy consumption. However, integration of sustainability measures to other supply chain planning problems, e.g., the production planning problem, has not gained that much attention. Such chain perspective would improve the possibilities for a proactive approach to sustainability: deciding on when and where to use certain recyclable packaging options to minimize the environmental impact of distribution, something which is currently lacking in the quantitative operations management literature.

Food quality is considered to a slightly larger extent, both in terms of the number of contributions and the variety of the methodologies used. Quality is often directly linked to the time that foods stay in storage before consumption. In food retail chains, the major quality loss usually happens during the times that foods stay in store shelves and consumer's fridge, as these constitute

a major share of the total time before consumption. However, there is not much to do in terms of operations planning to restrict this time-period. In the foodservice sector, however, food is usually prepared for immediate consumption without being stored for a long time. Thus, optimizing the operations of foodservice chains, which has not been much researched, can significantly influence consumers' perception of food quality. Current approaches towards quality improvement focus on the definition of limited shelf lives, as a restriction on the total time before consumption, or optimization of quality through explicitly defining and measuring quality decay in different stages of the chain. Looking into the related literature we can see that there is not much work on the trade-off between food quality and cost-related aspects (production, inventory and distribution) for highly perishable foods. Tracking and evaluating the quality of highly perishable foods in a supply chain must be done on a continuous basis, which significantly increases the complexity of modelling approaches. One potential way to deal with this complicacy is to develop appropriate hierarchical modelling and solution techniques based on proper aggregation and disaggregation schemes.

The results of our survey show that compared to the vast body of literature on the retail sector, research in the foodservice sector is still lacking behind. However, the foodservice sector is growing in size and importance due to, *e.g.*, the growing number of the elderly especially in the western society, changes in the work and dining culture, and the development of new concepts like meal provision at kindergartens and schools. Therefore, we focus on foodservice as the target food sector in the rest of this thesis to partly cover the research gap in the literature. The remaining research questions in this thesis are inspired by real case problems in the foodservice sector. Since the selected companies considered food quality as their main challenge, we focus on the quality aspect as the core food-related challenge among the discussed key challenges in food supply chain planning.

The main responsibility of the foodservice sector is to provide final consumers with prepared meals. Thus, produced meals are usually immediately consumed after delivery without being stored for a long time. This provides planners with more influence, compared to the retail sector, on the quality of the delivered products by coordinating production and distribution operations in a good way. The third chapter of this thesis is dedicated to investigating such quality improvement in a Danish foodservice company. Through explaining typical production and distribution operations in the catering sector and developing generic mathematical models, we show the complexity of this problem and the need for developing appropriate modelling and solution technique. We simplify the problem through a block-planning-based MILP model and decomposition procedure and analyse different planning scenarios. The presented numerical results indicate the benefits of taking an integrative approach towards production and distribution operations also in improving the quality of meals without drastically increasing the total costs. The results of our analysis also indicate that taking such an integrated planning approach is even more important when products are highly perishable.

In the foodservice sector, like in most other service industries, labour is an expensive capacity factor. Also, staff must possess certain skills to work on different production activities, and have to be trained to obtain new skills. Due to the broad range of required skills, decisions on the appropriate number of required staff with each skill is a challenging task. Further, a cost optimal

production and distribution plan, potentially leading to higher quality of delivered meals, cannot be achieved without coordinating the planning of workforce with production and distribution. The fourth chapter of this thesis illustrates this with an analysis on the design and operations planning for a municipal meal delivery system. A hierarchical planning methodology is developed, classifying design and operational decisions, supported by an MILP formulation for each decision class. The developed models are then solved through a tailor-made iterative procedure, which connects different decision classes, improves sub-optimalities and handles potential infeasibilities. The developed models and the solution algorithm for the case study result in managerial insights. Comparing the results of our integrated method with a non-integrated approach suggests a noticeable improvement especially in the number of staff hired on a temporary basis, and correspondingly the staffing cost, and also a sound reduction in the total costs. Furthermore, the impacts of combining a set of different decisions policies with our planning models are investigated on the selected key measures. This includes analysing shelf lives extension, transhipments penalty consideration, and pursuing different staff hiring strategies in our integrated models. The developed models and solution algorithm provide a solid basis for detailed scheduling of staff on a more operational level.

Next to the managerial insights obtained in the individual chapters, reading the whole thesis also suggests that in order to obtain better results from using advanced planning methodologies, specific characteristics of the foodservice sector have to be taken into account. Also, due to the strong interdependency of planning tasks in the foodservice sector, significant improvements can be achieved in key planning measures by integrating different planning tasks.

List of Abbreviations:

CSR	Corporate Social Responsibility
DC	Distribution Center
DKK	Danish Krone
ECR	Efficient Consumer Response
EFR	Emergency First Response
EPoS	Electronic Point of Sale
FAO	Food and Agriculture Organization
FIFO	First In, First Out
FTL	Full Truck Load
GDP	Gross Domestic Product
HACCP	Hazard Analysis and Critical Control Point
IMF	International Monetary Fund
IP	Integer Programming
ISO	International Standards Organization
IT	Information Technology
LNS	Large Neighborhood Search
LP	Linear Programming
LTL	Less than Truck Load
MILP	Mixed Integer Linear Programming
NH	Nursing Home
SKU	Stock Keeping Unit
SME	Small and Medium Enterprise
VRP	Vehicle Routing Problem

VRPTW	Vehicle Routing Problem with Time Windows
WCED	World Commission on Environment and Development

This thesis discusses and develops advanced planning methodologies to optimize operations in food supply chains, mainly focusing on the part of the chain which starts from the food processing industry: the food processing industry, the distribution industry, and final consumers. The thesis includes a thorough review classifying the related contributions and explaining how several key food distribution planning challenges have been dealt with in the Operations Management literature, followed by discussions about integration of production, distribution and workforce planning in the foodservice sector. At the end, the thesis summarizes the scientific and managerial conclusions of the research project and outlines possible future research directions.

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