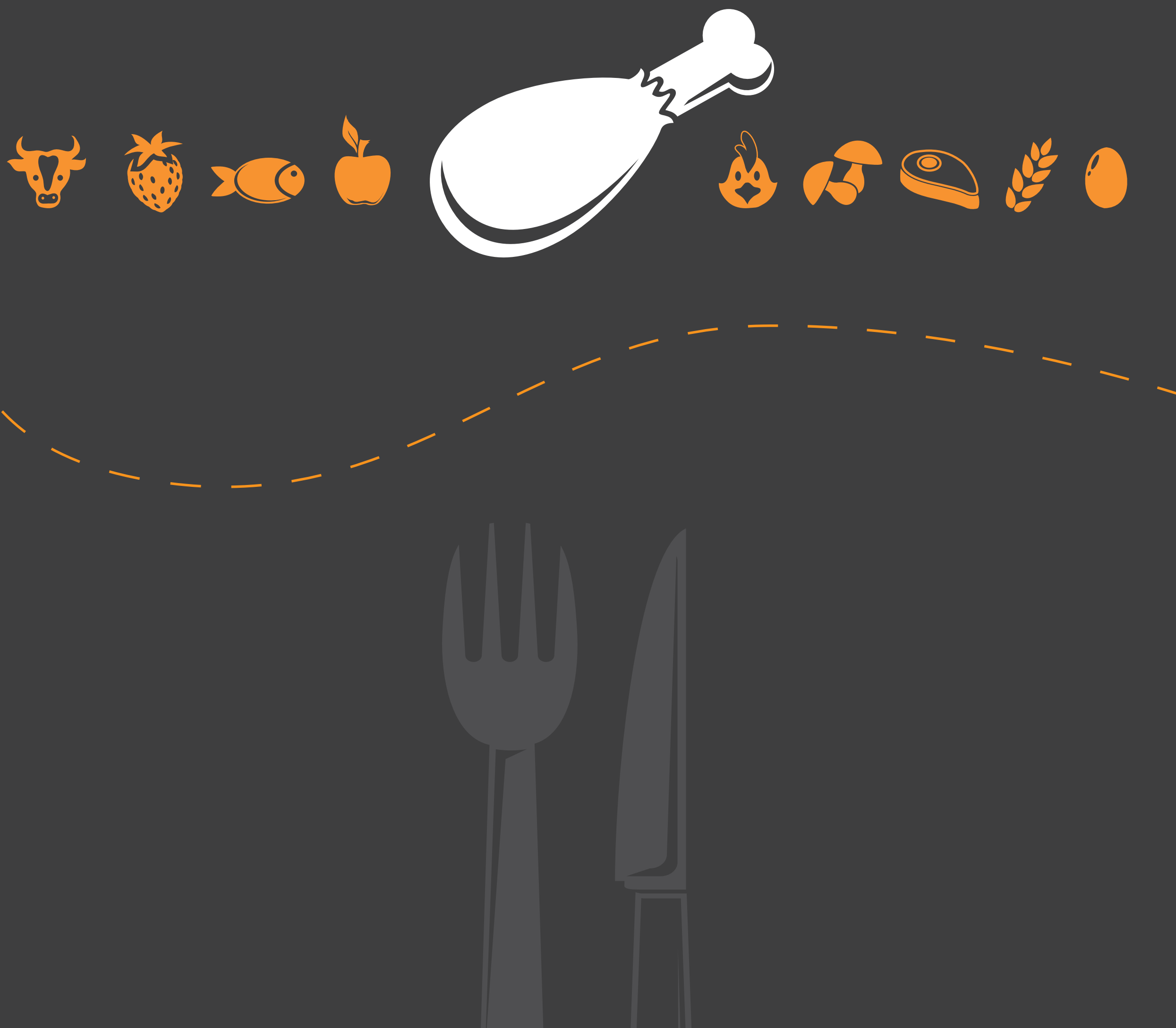
Effective use of product quality information in food supply chain logistics

Willem Antoon Rijpkema



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Wageningen, 6th May 2014 Willem Rijpkema

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General introduction to the research project

Willem A. Rijpkema

"Effective use of product quality information in food supply chain logistics"

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Introduction

The past few decades have seen remarkable changes in the organization and management of all stages of food supply chains [Shukla and Jharkharia, 2013]: an increase in farm size and efficiency [Fuglie et al., 2007], the development of international food supply chain networks, and consumers who are more demanding and critical regarding quality, safety, and availability of food products [Grunert, 2006]. As a result, globalized food supply chain networks are necessary to provide consumers with healthy, safe, high-quality food at low cost throughout the year.

To optimize their revenues, actors in food supply chains must match the many different quality traits of their food product supply (fat content, sweetness, quality maintenance) with consumers who appreciate those specific traits. This challenging task frequently leads to problems in current food supply chains, as can be concluded from the large quantity of food waste (about 35 % of worldwide food production is wasted [FAO, 2013a]), food scandals (e.g. dioxin crisis, horse meat scandal, BSE crisis), and frequent consumer dissatisfaction with the provided quality, price, and availability of food. Therefore, effective use of product quality information in the design and management of food supply chains is required to accommodate consumer preferences for food products of appropriate quality and to improve the effectiveness and efficiency of food supply chain operations [van der Vorst et al., 2011].

In the remainder of this chapter, the context of food supply chains is explained more broadly. Section 1.1 of this chapter provides an introduction to the contextual factors and current challenges in food supply chain management. In Section 1.2 the research objective and research questions are defined and it is described why this topic is interesting from both an academic and a societal point of view. This section is followed by a description of the research design (section 1.3), after which a thesis outline is provided in section 1.4.

1.1 Food supply chains

Food supply chains have characteristics that require specific management solutions, as several recent literature reviews have recognized [Akkerman et al., 2010, Bakker et al., 2012, Rajurkar and Jain, 2011]. This section provides a brief introduction into these characteristics and discuss how they affect logistics decision making in food supply chains. In section 1.1.1, a number of characteristics inherent to food supply chains and the nature of food products are discussed, whereas the main developments in food supply chains are presented in section 1.1.2. Food supply chain management is introduced in section 1.1.3, together with a discussion on the role of product quality information in food supply chain logistics.

1.1.1 Inherent characteristics of food supply chains

This section discusses inherent characteristics of food supply chains that affect logistics decision making. These inherent characteristics relate to food production, specific properties of food products, and processing characteristics of food products that affect logistics decision making throughout the entire food supply chain. A number of examples are presented for each of these sub-categories in the remainder of this section. For a more elaborate overview of characteristics and developments specific to food supply chains, the reader is referred to van der Vorst et al. [2005].

A number of characteristics common to food production affect logistics decision making [Akkerman et al., 2010]. For example, the quality, quantity, and periodic availability of food products varies widely because of the nature of food production (for example, dependence on natural conditions, availability of water, nutrients, and sunlight) [van der Vorst and Beulens, 2002]. Furthermore, as the production of many food products is seasonal, the production period is often long with limited flexibility in the quantity and quality of produce that will be harvested during this period. As a result, the availability, price, and quality of food products fluctuate strongly. Therefore, actors in food supply chains need effective planning mechanisms, and often rely on multiple sourcing regions, to deliver high quality food products to consumers throughout the year.

Food products also have specific properties that set them apart from most other products. For example, many food products are perishable, which means they are subject to decay or spoilage. To limit the effects of food quality decay, it is common in food supply chains to avoid long term storage, employ special management strategies such as expedited transport, use processing actions (e.g. drying, salting, and UV treatment), and adjust storage conditions (e.g. refrigeration, freezing, and modified atmosphere storage). Despite these efforts, recent research indicates that food losses and waste in Europe and North America on average account for 280 to 300 kilograms per capita, leading to an average emission of 700 kilograms of CO_2 equivalents per capita [FAO, 2013a].

Another common characteristic of food products is that their perceived quality consists of four central concepts: taste, health, convenience, and process characteristics [Grunert, 2005]. These concepts can be expressed using a large variety of quality attributes (e.g. product color, sweetness, fat content, salt content, mold presence, pesticide residue levels, adopted production methods), many of which are dynamic (i.e. they change over time under influence of environmental conditions). Some quality parameters may be easily determined (e.g. product weight), whereas obtaining accurate data on other quality parameters may be difficult (e.g. antibiotic residue levels, microbiological quality) because nondestructive measurement techniques are costly, inaccurate, or unavailable. The variety of food quality attributes, in combination with the difficulty of obtaining accurate information on these attributes, implies that food supply chain actors need effective mechanisms to supply consumers with products of an appropriate and consistent product quality.

Processing steps in food supply chains differ from most other processing industries. For example, many food products are derived from agricultural products, which implies that agricultural produce must be processed using a variety of steps, resulting in a number of end products originating from a single agricultural commodity (e.g. processed milk products or meat cuts). This so-called divergent production process means that multiple recipes may be used to process an agricultural commodity. Furthermore, the quality of ingoing products may affect the final product quality, processing yield, and required processing time. Food processors face a challenging task to optimize this match between a supply of products that varies in quality and a large number of (potential) end products. A factor that complicates this matching is the limited availability of processing equipment; because processing equipment is often costly, expensive to operate, and dedicated to specific actions, the available capacity is limited for most processing facilities. The availability of this processing equipment also may be limited by cleaning operations, which are required both in batch processes and semicontinuous production processes. Therefore, logistics decisions in processing actions may impact the effective capacity of processing equipment.

From this overview I can conclude that there are a number of inherent characteristics in food supply chains that complicate logistics decision making. The focus of this thesis is on two of these characteristics that have a large impact on the logistics management, design, and optimization of food supply chains: variability in product quality and the dynamics of food quality.

1.1.2 Developments in food supply chains

Besides characteristics that are inherent to food products and food production, developments in the previous decades have had a significant effect on logistics decision making. In this section, I discuss a number of these developments related to consumer preferences, food production and processing, and technology.

In previous decades, consumers have become more critical regarding food product quality [Grunert, 2006] and now demand high-quality, safe, healthy, and convenient food [van der Vorst et al., 2011]. In addition, consumers increasingly want year-round availability of fresh products in retail outlets. This demand has led to global sourcing of food products and a strong increase in long-distance transport of perishable products [Lee et al., 2012]. The consumer market is also experiencing further segmentation [Grunert, 2006], which is related to topics like taste and sensory characteristics, health, ease of use (convenience), and process characteristics (e.g. slaughtering methods) [Brunsø et al., 2013]. Also, consumers increased concern for the environmental impact of food production systems has resulted in demand for local organic products and pressure on food supply chain actors to improve the sustainability of their activities.

The food production column also has experienced remarkable changes. In the past century, the scale intensity of food production has grown considerably as a result of mechanization and price mechanisms. For example, in the United States between 1950 and 2000, the average amount of milk produced per cow increased from 2410 to 8255 kilograms per year (+242%), the average yield of corn rose from 1.40 tons to 5.49 tons per hectare (+292%), and farmer productivity per hour worked increased 1200 % [Fuglie et al., 2007]. Average farm size also has grown at a high rate; the average Dutch pig farmer had 504 fattening pigs in 2000, which grew to 1180 in 2012 [PVV]. This has had a significant effect on the number of farms and how

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they are organized. Similarly, the food processing industry has experienced scale intensification. As a result, a large share of all produced food is now processed by a limited number of global food processors (e.g. VION Food Group, Royal FrieslandCampina). This scale intensification in food production and processing allows actors in the food supply chain to increase the professionalism of their operations, invest in innovative technology and supply chain networks, and operate on a global scale. In addition, the organizational focus and performance focus have changed in response to changes in consumer requirements, as shown in Figure 1.1.

Many food supply chains are experiencing a rapid globalization. For example, the export value of fish products from China to the United States increased from 0.63 billion US$ in 2000 to 2.58 billion US$ in 2010, and in the same period, the export value of meat from the European Union to Russia increased from 0.99 billion US$ to 3.87 billion US$ [Lee et al., 2012]. These figures indicate that food supply chain actors increasingly rely on international and global sourcing, which implies that they need to develop effective strategies for (perishable) food products.

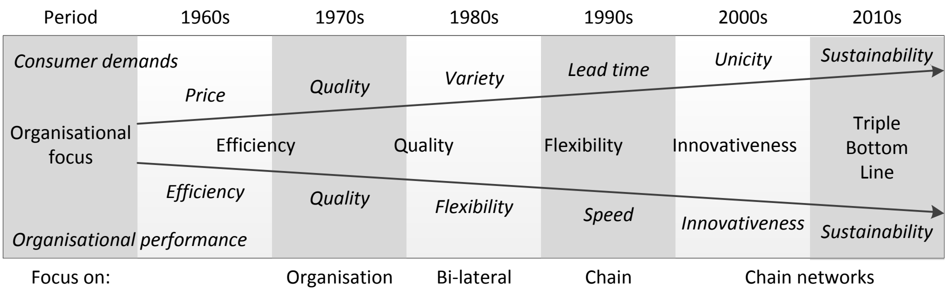

Figure 1.1: Market and company requirements throughout time (van der Vorst [2011].

A key enabler for improvement of logistics control in food supply chains is the development of information and communication technology (ICT) and sensory technology. These developments provide the means to gather, communicate, and process information more effectively [Kumar et al., 2009]. In turn, food supply chain actors are able to measure, monitor, and communicate product quality information throughout the supply chain and use this information to support their logistics decision making.

To conclude, there are a number of developments in consumer markets, the food production column, and available technology that have affected logistics decision making in food supply chains. The combination of developments in food supply chains with the natural variability in product quality provides opportunities for food supply chain actors to add extra value [Grunert, 2006]. However, effective logistics decision making is required to satisfy diversified consumer segments with food products of appropriate quality.

1.1.3 Food supply chain management

A supply chain (SC) consists of all parties directly or indirectly involved in fulfilling a customer request. The SC includes not only the manufacturer and suppliers, but also transporters, warehouses, retailers, and even customers themselves [Chopra and Meindl, 2007]. Effective SC operations require integrated management throughout the entire supply chain, also called supply chain management. Supply chain management (SCM) encompasses a variety of planning and management activities, like sourcing, procurement, conversion, logistics management, and coordination and collaboration with channel partners (Council of Supply Chain Management Professionals). Central in SCM is the coordination of processes and the exchange of information between partners in the supply chain, which has received increasing attention in the operations research and operations management literature in the last two decades [Christopher, 2011, Simchi-Levi et al., 2007].

Food supply chain management (FSCM) is the term given to the system and interconnections of organizations, people, activities, technologies, information, and resources involved in production and distribution of a food product (Institute of Food Science & Technology). The specific characteristics of food supply chains require SCM to aim not only to improve logistics performance (e.g. cost and delivery service requirements), but also to preserve food quality and to deliver products of the right quality at the right place and time [van der Vorst et al., 2011]. A schematic overview of the different activities in food supply chains is presented in Figure 1.2. This overview is based on the Supply Chain Operating Reference (SCOR) model, developed by the Supply Chain Council for assessing supply chains. The SCOR model distinguishes five management processes: plan, source, make, deliver, and return. These five processes are complicated by the specific developments and characteristics of food supply chains discussed in the previous sections. This complexity creates new opportunities for food supply chain actors to add value [Grunert, 2006], although many of them struggle with this, as demonstrated by i.) large amounts of food waste [Gustavsson et al., 2011], ii.) poor customer satisfaction, iii.) low profit margins, and iv.) food scandals (e.g. the BSE, dioxin, or horse-meat crises). To deal with the complex environment of food supply chains and to improve the effectiveness of logistics decision making, effective logistics decision making is required.

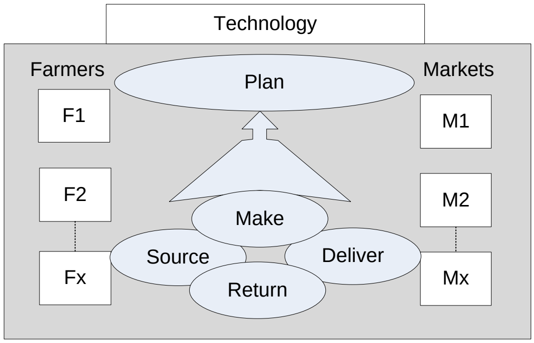

Figure 1.2: Schematic overview of Food Supply Chain Network.

A number of disciplines help to facilitate effective logistics decision making in food supply chains. First of all, logistics management strategies, called *food logistics management* (FLM), are necessary to deal with the specific characteristics of food supply chains. Based on the Council of Supply Chain Managements definition of logistics management, FLM can be defined as that part of supply chain management that plans, implements and controls the efficient, effective, forward, and reverse flow and storage of food products, food services, and related information between the point of origin and the point of consumption in order to meet customer requirements.

A key characteristic in meeting customer requirements is delivering products of appropriate quality. To deal with quality characteristics specific to food supply chains, such as dynamic product quality or variability in product quality, *quality management* (QM) practices need to be integrated in FLM practices. Quality management is defined by Luning and Marcelis [2009] as the total of activities and decisions performed in an organisation to produce and maintain a product with the desired quality level against minimal costs. According to Jurans quality trilogy [Juran, 2005] these activities include quality planning, quality control, and quality improvement. Therefore, QM is the act of overseeing all activities and tasks needed to maintain a desired level of excellence, which includes creating and implementing quality planning and assurance, as well as quality control and quality improvement.

As FLM decisions are often complex, advanced *decision support models* (DSMs) may be required to support FLM decisions and integrate QM practices in logistics decision making. A variety of quantitative DSMs can be used to support logistics decision making in food supply chains [Akkerman et al., 2010]. Several types of DSMs may be developed, relying often on simulation or optimization approaches, or a combination of both. Decision making under uncertainty has an important influence on the effective configuration and coordination of supply chains, and this uncertainty tends to propagate up and down the SC, appreciably affecting its performance [Peidro et al., 2009]. Several quantitative approaches to deal with uncertainty in decision making are available, including analytical models, simulation models, and hybrid models [Peidro et al., 2009]. The most appropriate DSM to support decisions is case specific.

From the previous paragraphs, we may conclude that effective FLM approaches are required to provide consumers with products of appropriate quality, and in turn, QM practices must be integrated with the FLM approaches. In addition, DSMs may be required to obtain efficient solutions and assess their effectiveness. This thesis research contributes to the literature by presenting several case studies in which advanced product quality information was used to support logistics decision making. The research was narrowed to study two important types of decisions, product sourcing and process design, and two quality-related characteristics of food products, namely variability in quality and dynamic quality decay. The combination between the type of supported decision, the specific quality characteristic, and the resulting case study can be found in Table 1.1. The focus of this thesis is on the effective management and design of distribution and processing systems in food supply chains. The mechanisms driving farmer production systems and consumer demand are beyond the scope, although the effect of these characteristics on distribution and processing systems are included.

Table 1.1: Overview of the research questions.

	Process design	Product sourcing
Variability in product quality	Case study 1	Case study 2
Dynamic product quality	Case study 4	Case study 3

1.2 Research objective

This section discusses the objective of this thesis. First, the research context is described in section 1.2.1, followed by a brief research statement in section 1.2.2 and the research questions in section 1.2.3.

1.2.1 Research context

Use of advanced product quality information in design and management of effective food supply chains may have a variety of benefits. The information may help reduce food waste by improving the match between supplied and demanded quality features, which in turn, could lead to more efficient use of resources, reduction of global hunger, and improved economic sustainability [FAO, 2013a]. Effective use of product quality information in logistics decision making also may allow food supply chain actors to satisfy increasingly demanding and segmented consumers by providing products of the right quality, in the right quantity, at the right moment [van der Vorst et al., 2011]. In addition, presenting customers with fresher products of higher quality may improve the safety of food products, which could reduce the risk of food-borne illnesses. As such, the development of innovative logistics control concepts for food supply chains has the potential to contribute to a better quality of life at lower cost.

Acknowledging the importance of supplying consumers with safe, high-quality food products, the European Union supports several research projects that aim to improve the effectiveness, sustainability, and safety of food supply chains. Two of these projects *Q-porkchains* and *Veg-i-Trade* have supported this research.

Q-porkchains is an EU-funded Framework Programme 6 for Research, Technological Development and Demonstration Activities. Partners from industry, research institutes, and universities collaborated in this project to ensure the future quality of pork meat through development of sustainable production, processing, and distribution systems. The *Q-porkchains* project was divided into eight modules, each of which targeted a specific research area (e.g. product development, product quality, or consumer preferences). My research fell within the module for integration and sustainable management of pork supply chains and focused on the design of logistics models and sustainability solutions for European pork chains. In particular, DSMs were developed to support evaluation of production and distribution network scenarios using multiple performance indicators like costs, energy use, product quality, and logistical performance. Collaboration was frequent with those working in other modules to assess the impact other modules (e.g. innovative sensory equipment and changes in consumer preferences) may have on production, processing, and distribution systems in pork supply chains. For more information on the *Q-porkchains* project and the individual modules, see the project website: `http://www.q-porkchains.org/`. Outputs in this thesis stemming from research conducted in the context of *Q-porkchains* include Rijpkema et al. [2012], Rijpkema et al. [to appear], and Rijpkema et al. [submitted,a].

Veg-i-Trade is a seventh EU-framework project aimed at the development of tools to prevent and/or control the microbiological risks of fruits and vegetables associated with changing consumption patterns, globalization, and climate change [Jacxsens et al., 2010]. The research project assesses the economic structure of the fresh produce chain and develops control measures to minimize microbiological and chemical risks. To achieve these goals, 11 separate work units assess various aspects of food safety in vegetable and fruit supply chains. The work units cover a wide range of topics, such as consumer trends, agronomical practices, and water treatment technology. The research presented here was performed within work unit in which a simulation model was developed to assess the impact of different logistics systems designs (scenarios) on specific product quality parameters and total logistics costs. This dynamic integrated model allows for an evaluation of the impact of different logistics scenarios on logistics costs and product quality parameters. Frequent collaboration with other work units was done to assess the impact other units research (e.g. microbiological growth models and data on initial product quality) may have on production, processing, and distribution systems in international fruit and vegetable supply chains. For more information on the *Veg-i-Trade* project and the individual work units, see the project website: `http://www.veg-i-trade.org/`. Outputs in this thesis stemming from research conducted in the context of *Veg-i-Trade* include Rijpkema et al.

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[2014], and Rijpkema et al. [submitted,b].

1.2.2 Research statement

My overall objective in this thesis is to assess the added value of using product quality information in logistics decision making in food supply chains. I focus on the interrelation between logistics decision making processes and two characteristics commonly observed in food supply chains: dynamic product quality and variability in product quality. Within this research, logistics decisions were supported in a number of case studies defined within the scope of the *Q-porkchains* and *Veg-i-Trade* projects. In each case study, product quality information was exploited to improve the overall supply chain performance. This quality information was integrated into FLM strategies, and the potential impact of these strategies was assessed and optimized using quantitative DSMs. The empirical objective was to analyze the opportunities that using advanced product quality information in food supply chains may present.

The main hypothesis of this PhD thesis is:

> Effective use of product quality information in logistic decision making has the potential to improve overall performance in food supply chains.

1.2.3 Research questions

The main research question of this thesis, studied in both the *Q-porkchains* and the *Veg-i-Trade* projects, was:

> How can the effectiveness of logistics decision making in food supply chains be improved using advanced product quality information?

The main research question was explored using four case studies: two in the *Q-porkchains* project (pork supply chains) and two in the *Veg-i-Trade* project (fruit and vegetable supply chains).

Case study 1

The first stage of this research concerned meat supply chains, in which the ongoing goal is to deliver high-quality products to satisfy increasingly demanding consumers. To add consumer value and satisfy increasingly demanding and segmented consumers, meat processors must exploit the variability in product quality of their product flow [Grunert, 2005]. Therefore, acquiring and using product quality information in logistics decision making is very important, although the literature has not yet given much attention to this area [Akkerman et al., 2010].

A commonly observed characteristic in food supply chains is variability in product quality of agricultural products (e.g. variation in weight or fat content). New technology makes it possible to gather and use more product quality information in logistics decision making [Kumar et al., 2009]. However, sorting for these quality features increases processing complexity and generates a need for flexible and agile supply chain design. Although most research has identified supply chain flexibility solely as a positive characteristic, there is a limit to the degree to which a supply chain can be flexible while meeting demand and operating efficiently [Stevenson and Spring, 2007]. Previous research has suggested that decision makers should carefully assess how measures to increase flexibility might affect profitability and efficiency before investing in them [He et al., 2011].

To add to the literature on use of product quality information in logistics decision making and to gain more insight in the trade-off between flexibility and efficiency while sorting products to segmented consumer markets, I posed the following research question:

RQ1: How can differentiated consumer segments be served efficiently through sorting for more product quality features?

Chapter 2 presents an exploration of this research question, based on the article, Process redesign for effective use of product quality information in meat chains, published in the *International Journal of Logistics: Research and Applications* (Volume 15, Issue 6, pp. 389-403, 2012) ([Rijpkema et al., 2012]).

Case study 2

This project also examined variability in product quality at a large meat processing company involved in *Q-porkchains*. This company faced variation in the quality features of animals delivered for processing (e.g. weight and meat leanness), which resulted in variation in processing performance and final product quality. A process analysis revealed that the company did not gather any information on the quality of livestock that individual farmers delivered until the animals arrived at the slaughterhouse. This lack of information prior to delivery resulted in uncertainty in product quality at individual slaughterhouses. Reducing this uncertainty could be beneficial because decision makers would be able to improve the match between supplied products and end consumers. This study assesses whether product quality information gathered in earlier deliveries could be used to reduce uncertainty in received product quality. First, the use of historical quality information for support of logistics decision making was studied. The following research question resulted:

RQ2A: Can historical quality delivery data from farmers be used to improve sourcing decisions in food supply chains?

The second research area studied in this case study was multi-objective stochastic programming. The decision maker would like to find efficient sourcing solutions that balance conflicting performance objectives: logistics costs and deviations from required product quality. To obtain these sourcing solutions, a stochastic programming problem was developed to exploit historical farmer delivery data. Use of quantitative models to support operational and tactical sourcing decisions has received little research attention, according to a recent literature review on quantitative models for supply chain planning under uncertainty by Peidro et al. [2009]. Therefore, the following research question was posed:

RQ2B: How can efficient solutions that provide a trade-off between different performance indicators be obtained using stochastic optimization?

Research questions 2A and 2B are discussed in chapters 3 and 4; chapter 3 is based on the article, Application of stochastic programming to reduce uncertainty in quality-based supply planning of slaughterhouses, accepted for publication in the *Annals of Operations Research* ([Rijpkema et al., to appear]). Chapter 4 is based on the article, Bi-criterion procedures to support logistics decision making: Cost and uncertainty, submitted for publication in a scientific journal ([Rijpkema et al., submitted,a]).

Case study 3

Besides case studies in meat supply chains, I also conducted studies in fruit and vegetable supply chains through the *Veg-i-Trade* project. In fruit and vegetable supply chains quality decay is responsible for large quantities of food waste [FAO, 2013a]. Poor coordination among supply chain actors along with inefficient retail practices have been identified as important causes of food waste [Gustavsson et al., 2011]. A recent literature review on perishable inventory management by Bakker et al. [2012] indicated that few studies have taken into account the dynamic and stochastic nature of product quality decay while sourcing products.

Product sourcing is based on the adopted sourcing strategy, which encompasses a variety of factors such as the number of contracted suppliers, the relationship with suppliers, and the contract type and conditions negotiated [van Weele, 2009]. The most suitable sourcing strategy depends on the organizations strategic objectives and characteristics, as well as its supply chain. Once a sourcing strategy has been chosen, the actual ordering (i.e. the placement of purchase orders under previously arranged conditions) can take place. The quantity ordered is determined using an order policy, which typically attempts to balance performance objectives such as flexibility against shelf availability and cost. Therefore, the sourcing strategy and order policy may enhance product sourcing in perishable product supply chains that struggle to provide high-quality products. Despite the potential advantages of advanced sourcing strategies and order policies to perishable product supply chains, their use has been very limited. In this case study, it was hypothesized that: (i) existing sourcing strategies that do not take perishability into account may perform ineffectively in perishable product supply chains; and (ii) robust performance improvements can be achieved in perishable product supply chains by including costs for expected quality decay in logistics decision making. To test these hypotheses, the following research question was posed:

RQ3: How can advanced product quality information be used to improve product sourcing in perishable product supply chains?

Chapter 5 presents the study results of this research question, which is based on the article, Effective sourcing strategies for perishable product supply chains, published in the *International Journal of Physical Distribu-*

tion & Logistics Management (Volume 44, Issue 7, 2014) ([Rijpkema et al., 2014]).

Case study 4

A specifically designed supply chain is required to supply consumers with fresh products of high quality while minimizing overall costs and product waste [Ahumada and Villalobos, 2009, van der Vorst et al., 2009]. As mentioned earlier, an ineffective design of perishable product supply chains may lead to poor product quality, and ultimately food waste. To minimize food waste, agricultural produce must reach consumers efficiently [FAO, 2013b], and effective supply chain design and management are required with specific strategies for food waste reduction [Rajurkar and Jain, 2011]. Research in the UK identified several causes for food waste in the supplier-retailer interface, including (i) a combination of poor forecast accuracy and short shelf-life and (ii) retailers that balance on-shelf availability and waste [Mena et al., 2011].

In the *Veg-i-Trade* project, the idea arose to assess whether a common supply chain strategy called postponement might be reduce food waste in the vegetable supply chain. Postponement refers to the practice of delaying supply chain activities until a demand is realized [van Hoek, 2001]. Research suggests that postponement can be used to deal with large demand variety to improve responsiveness while reducing transportation expenditures, inventory levels, and product obsolescence [Lee and Billington, 1994]. There are several types of postponement, with form postponement (FP) being the most common. The main idea of FP is to maintain products in a neutral, noncommitted status as long as possible and to customize them at the latest possible moment [Yang et al., 2004]. Although there has been quite some research on postponement practices (see literature reviews by van Hoek [2001] and Boone et al. [2007]), the number of studies of FP in food supply chains is limited [van Kampen and van Donk, 2013]. Therefore, the effect of typical food processing industry characteristics on the applicability of FP is unclear [van Kampen and van Donk, 2013]. One of these characteristics is the perishability of food products: Although it is commonly accepted that FP is an effective way to reduce inventory levels, the effect FP may have on food quality and product waste has not been studied, to the best of my knowledge. Because of this gap, the following research question was posed:

RQ4: Can form postponement be used to limit food waste and quality decay in food supply chains?

This research question is discussed in chapter 6, which is based on the article, The effect of form postponement in the reduction of waste in food supply chains, submitted for publication in a scientific journal ([Rijpkema et al., submitted,b]).

1.3 Research design

The main objective of this thesis research is to assess the added value of using product quality information in logistics decision making in food supply chains. To achieve this objective, four research questions were introduced and studied in four separate case studies. Experts from industrial partners, research institutes, and universities were called upon to support these case studies, and numerical data used also was obtained from these industrial partners.

In each of the case studies, a number of techniques were applied, employing both qualitative and quantitative methodologies supported with adequate literature. Both inductive and deductive research methods were used, supported by literature research and explorative case studies. Each of the case studies involved a number of methods to arrive at a quantitative decision support system, which are summarized in Table 1.2. A detailed description of the applied methods can be found in the respective chapters.

1.4 Thesis outline

This thesis includes a collection of five papers that contribute to my overall objective: to assess the added value of using product quality information in logistics decision making in food supply chains. This thesis is organized as follows:

Chapter 2 presents research question 1 through a case study investigating operational sorting performance at a meat processing company. This case study involved sorting meat products for a specific quality feature called water holding capacity. A process and data analysis was performed

1

Table 1.2: Applied methods.

Research question	Chapter	Applied methods
1	2	Process and data analysis
		Scenario-analysis
		Discrete event simulation
2A + 2B	3 and 4	Supply chain analysis
		Data analysis
		Optimization heuristics
		Stochastic programming
3	5	Supply chain analysis
		Optimization heuristics
		Scenario-analysis
		Discrete-continuous simulation modelling
4	6	Supply chain analysis
		Scenario-analysis
		Discrete-continuous simulation modeling

to gain insight into the processing chain and to identify improvement opportunities, which were used to develop scenarios for future operations. These scenarios were assessed using a discrete event simulation tool.

Chapters 3 and 4 present research questions 2A and 2B through a case study performed in collaboration with a large meat processor. This case study investigated the use of historical delivery data from farmers to improve slaughterhouse allocation plans. To do so, the supply chain of the meat processor and operational data was analysed. Stochastic programming that exploited historical product quality information were developed to find improved allocation plans. In addition, heuristics procedures were developed to generate efficient solution sets that balanced multiple performance dimensions.

Chapter 5 presents research question 3 through a case study investigating sourcing policies in an international strawberry supply chain, and including an analysis of the respective supply chain. Scenarios for future operations and used optimization heuristics were developed to obtain sourcing policies for this strawberry supply chain. The effectiveness of these sourcing policies was assessed using a discrete-continuous chain simulation tool that included quality predictive models.

Research question 4 is presented in *chapter 6* through a case study investigating the application of form postponement in an international lettuce supply chain, including an analysis of the respective supply chain. Several scenarios for application of form postponement were defined, and the effectiveness of these scenarios was assessed using a discrete-continuous chain simulation tool that included quality predictive models.

In *chapter 7*, I discuss the overall findings of this thesis, and discuss the research questions. The main research question is addressed through a synthesis of the findings of the case studies with findings in the literature. In addition, the scientific contribution and managerial implications of this research are discuss and recommendations for further research are presented.

Chapter 2

Process redesign for effective use of product quality information in meat chains

In this chapter we study research question 1:

> *How can differentiated consumer segments be served efficiently through sorting for more product quality features?*

This chapter is based on the published journal article:

Rijpkema, W.A., Rossi, R., and van der Vorst, J.G.A.J., International Journal of Logistics: Research and Applications, 2012, Volume 15, Issue 6, pp. 389-403.

Abstract

To fulfil segmented consumer demand and add value, meat processors seek to exploit quality differences in meat products. Availability of product quality information is of key importance for this. We present a case study where an innovative sensor technology that provides estimates of an important meat quality feature is considered. Process design scenarios that differ with respect to sorting complexity, available product quality information, and use of temporary buffers are assessed using a discrete event simulation model. Results indicate that increasing sorting complexity by use of advanced product quality information results in a reduction of processing efficiency. Use of production buffers was found to increase processing flexibility and mitigate negative effects of high sorting complexity. This research illustrates how the use of advanced product quality information in logistics decision-making affects sorting performance, processing efficiency, and the optimal processing design, an area that has so far received little attention in literature.

Keywords product quality information, food supply chains, manufacturing flexibility, simulation, meat

2.1 Introduction

As witnessed in several recent studies [Grunert, 2006, Akkerman et al., 2010], there is a growing interest from retail and consumer organisations in high-quality, healthy and convenience food. As a result, demand for product quality features such as colour or taste has become more segmented and product variety has increased significantly. This provides food processors with the opportunity to add extra value by adjusting their production strategies to serve segmented demand [Grunert, 2006]. In order to serve segmented consumers, demand preferences of customer segments must be translated into clear process and production specifications for food processors [Grunert et al., 2004, Perez et al., 2009]. Furthermore, supplied products must be sorted and processed to different customer segments that value specific product quality features most. The flexibility of the supply chain design to sort products to end market demand, of course, must allow for the effective exploitation of available product quality information.

Recent developments in information and communications technology and sensing technology have improved the means to gather, communicate and process product quality information [Kumar et al., 2009]. These innovative technologies allow processing companies to gather and use advanced product quality information in their planning processes [Chen and Tu, 2009]. This allows food processors to identify products suitable for premium segments, and offers opportunities for more advanced sorting of food products. Sorting to a larger number of segments will, however, also increase the complexity of product sorting and processing, which might reduce processing efficiency and increase the demand for processing flexibility. A higher sorting complexity might, therefore, make a more flexible process design favourable, for instance, by introducing slack in production by use of buffers [Hallgren and Olhager, 2009].

In a literature review on quantitative operations management approaches in food supply chains, Akkerman et al. [2010] found some evidence of the use of product quality information in logistics decision-making in food supply chains, but this remains a challenging research area. We contribute to this field of literature by assessing use of advanced product quality information in product sorting at a meat processor. This chapter presents a case study of a large European meat processing company. The company faces variation in quality features of animals delivered to them (e.g. weight, meat leanness), resulting in variation in processing performance and final product quality. We consider the use of an innovative sensor technology to sort for an advanced meat quality feature, the water holding capacity (WHC), that affects sensory appearance and processing characteristics of meat products. The WHC is usually measured by the vapour loss over a period of time, also known as drip loss [Forrest et al., 2000]. Products with a low or a high drip loss generally cause more problems during processing and consumption, although the magnitude of problems caused by high or low drip losses depends on the type of end product [O'Neill et al., 2003]. Until recently, there was no low-cost, fast, non-destructive and accurate method to determine WHC under commercial conditions. Recent research has identified an innovative sensor based on near infrared spectroscopy technology (NIRS) as a suitable method to estimate WHC in meat products [Prevolnik et al., 2010]. A review article on applications of NIRS revealed that this technique is used to assess quality features of a variety of food products [Huang et al., 2008]. The work by Huang et al. does, however, not discuss the effects of acquiring more product quality information on the sorting performance and complexity. In this case study, we, therefore, assess the use of NIRS-estimates of WHC in sorting for advanced product quality features. Since product quality estimates provided by a sensor will involve some estimation errors, not all products will be sorted correctly. Moreover, as sorting for advanced product quality information increases sorting complexity, the use of an alternative, more flexible, processing layout may be more favourable. A simulation model was developed to test how sorting for advanced product quality information affects sorting performance and processing efficiency. The option to use product sorting buffers was also included to assess how sorting complexity affects performance of systems with or without sorting buffers. Process designs that differ with respect to product sorting complexity, availability of product quality information, and use of these sorting buffers are analysed using this simulation model.

The chapter is structured as follows. First, a review of current literature was used to gain insight into topics relevant to this case study (Section 2.2). This review includes topics such as supply chain flexibility, supply chain redesign strategies, performance measurement, and application of modelling techniques in food supply chains. The literature review is followed by an analysis of the processing chain of the industrial partner, followed by a detailed analysis of the processes we consider in this case study. The findings of this process analysis are given together with process design scenarios and key performance indicators (KPIs) in Section 2.3. Section 2.4 discusses the simulation model elements, model inputs, and the simulation example.

The simulation results are given in Section 2.5, and the discussion and conclusions in Section 2.6.

2.2 Theoretical framework

In recent years, there has been much emphasis in industry and academic literature on the reduction of supply chain inefficiencies, which has resulted in a variety of management principles such as just in time [Mackelprang and Nair, 2010]. This led to the so-called lean paradigm, which considers the expenditure of resources for any goal other than end customer value creation to be wasteful [Shah and Ward, 2007]. Whereas the focus of the lean paradigm is mainly on eliminating waste, in other supply chains, a trend towards responsiveness to fluctuating customer demand and market turbulence is observed, also called supply chain agility [Gunasekaran et al., 2008]. Which strategy is most effective depends on the supply chain characteristics; in supply chains with primarily functional products with low demand uncertainty the focus should be on efficiency and leanness, whereas for products with unpredictable demand and high levels of product variety, a supply chain design with a focus on flexibility and agility is more appropriate [Christopher and Towill, 2000].

Flexibility in processing is, therefore, of key importance for supply chains that face great uncertainty and variability in demand. A variety of redesign principles are available to increase flexibility and responsiveness of supply chain planning and control, such as allowing time and capacity in plans and operations by use of product buffers [Klibi et al., 2010]. Supply chain flexibility is seen solely as a positive supply chain characteristic in many literature contributions, although there is a limit to the degree to which a supply chain can be flexible whilst meeting demand and operating efficiently [Stevenson and Spring, 2007]. Decision-makers should carefully assess the effect of measures to increase flexibility on profitability and efficiency before investing in them [He et al., 2011]. For example, when buffering products, capital costs are incurred. Specific food supply chain characteristics (e.g. low level of innovation, mature markets, low levels of added value) make a lean process design favourable. However, other characteristics (e.g. perishability, high demand variability) require food processors to be flexible and responsive in manufacturing. Furthermore, many food products have a divergent production process (i.e. the product is disassembled rather than assembled), where more product quality information is available after each processing step. The combination of these specific characteristics makes it difficult for food processors to adopt either a lean or an agile process design, and requires food processors to be both efficient and flexible [van der Vorst et al., 2001].

Grunert [2006] indicates that food processors may add extra value by serving advanced customer segments. This will increase the complexity that food processors face, and requires them to adopt a more flexible and agile supply chain design. Furthermore, a specific focus on use of product quality information in product sorting is necessary. This focus incorporates acquiring product quality information, understanding food systems and consumer preferences, and use of decision support models to improve food quality and product availability throughout the supply chain [van der Vorst et al., 2011]. An extensive literature review of quantitative operations management approaches and challenges in food distribution by Akkerman et al. [2010] concludes that use of product quality information in decision-making in food supply chains can be seen in some recent work, but that it remains a challenging research area. From this literature review, we conclude that some characteristics of food supply chains require a specific focus on product quality information. Combined with market trends towards segmented consumer markets in food supply chains, this leads to the conclusion that food processors need more processing flexibility to satisfy demanding customers and add extra value. New technological developments make it possible to gather and use more product quality information. These changes in markets and technologies might, therefore, lead food processors to redesign their supply chain to increase the variety of products they produce by advanced sorting for product quality.

2.3 Case description

This section gives an overview of the processing chain that is analysed in this case study. The process analysis is based on a number of visits and interviews with knowledgeable company personnel. Setting of KPIs, development of process design scenarios, and intermediary results are discussed with company experts such as operations management staff, production planners, plant managers, and quality managers to ensure validity of our findings.

A description of the supply chain under consideration in this case study is given in Section 2.3.1. Section 2.3.2 provides a detailed analysis of the processing steps that we consider in this case study. Section 2.3.3 describes the process design scenarios that we compare in this study, which are assessed based on performance indicators discussed in Section 2.3.4.

2.3.1 Supply chain description

We present the processing chain of a large European meat processor owning multiple slaughterhouses and processing locations. This processor buys livestock that are slaughtered, processed, and delivered to retail and wholesale companies. An overview of the consecutive processing steps performed at the slaughterhouse is given in Table 2.1. In the processing steps where the throughput-time is either very short, or the capacity is not limiting in the processing line this is indicated by . This involves, among others, killing, cleaning, eviscerating, veterinary inspection, and carcass grading. During the slaughtering process, each animal is converted into two carcasses (i.e. half animals) with measured product quality features (i.e. weight, fat thickness, lean meat ratio, muscular quality, and gender).

Table 2.1: Processing steps.

Process	Process duration	Capacity	Product
Slaughtering	Approx. 20 min	560 pigs per hour	Carcass
Carcass sorting	-	1120 carcasses/hour	Carcass class
Carcass cooling	15 h or more	-	Chilled carcass classes
Carcass cutting	-	1200 carcasses/hour	Carcass parts
Sorting of carcass parts	-	1200 carcasses/hour	Sorted carcass parts
Buffering of carcass parts	Variable	-	Buffered carcass parts

After slaughtering carcasses are sorted into separate carcass classes based on the product quality features. Carcass classes are used to create a preliminary match between a group of carcasses and potential end products and markets. Although generic information on carcass quality features does not give a perfect prediction of the product quality of individual carcass parts, it is still useful to make a rough match between carcasses classes and end products. Sorting of carcasses is synchronised with the rate of slaughtering at approximately 1120 carcasses per hour. Sorted carcasses are chilled overnight, after which the carcass classes are transferred class by class to the processing room. Carcass processing starts with the primal cut, which divides the carcass into several main parts. After the primal cut, product quality information of individual parts (e.g. weight, fat thickness) is gathered. Based on the product quality information that is available, individual carcass parts are sorted to end-product groups. The sorted carcass parts can be either processed directly or be processed after temporary storage. For the temporary storage of carcass parts, these need to be transferred to a storage facility, which involves manual labour.

Carcass parts are customised to order specifications by a number of processing steps (e.g. debone, trim fat, remove tail, and remove tailbone). These processing steps are performed at a number of processing stations, and involve manual labour. Since the processing steps are highly standardised, employees that perform this manual labour can be transferred from one processing station to the next with limited transfer time. If, however, several end-product groups are processed simultaneously all processing stations required in production of at least one of the end-product groups need to be manned, regardless of the rate at which they are operating.

2.3.2 Process analysis

In this case study, we consider sorting and processing of hams. We will, therefore, focus on a description of the processing chain from carcass cutting to processed hams in the remainder of this section.

A schematic overview of the ham processing chain is given in Figure 2.1. The carcass classes slaughtered the day before are chilled and available in the cooling room. Planners combine information on available carcass classes with information on demand for ham products to make a preliminary match between each of the carcass classes and demanded ham products. Each ham originating from a carcass class is currently matched with a limited number (24) of end products, based on the expected quality of hams originating from a particular carcass class (e.g. a fat carcass on average yields a fat ham), and the demand for ham products. As an example, a ham originating from carcass classification X may be allocated to ham product A if it has more than 25 mm of fat and a weight above 13 kg. The ham will be allocated to product B if it has between 18 and 25 mm of fat and a weight between 12.8 and 15 kg. If the ham does not fit the specifications of product A or B it will be allocated to product C.

After the preliminary match between carcass class and ham products is made, the carcasses are cut into parts by the primal cut. After the primal cut, a more detailed quality information of individual carcass parts is gathered (e.g. ham fat thickness, ham weight). Based on the gathered product quality information and the quality specifications of ham product groups matched with that particular carcass class, each ham is sorted to an end product. In the current processing system, three ham quality features

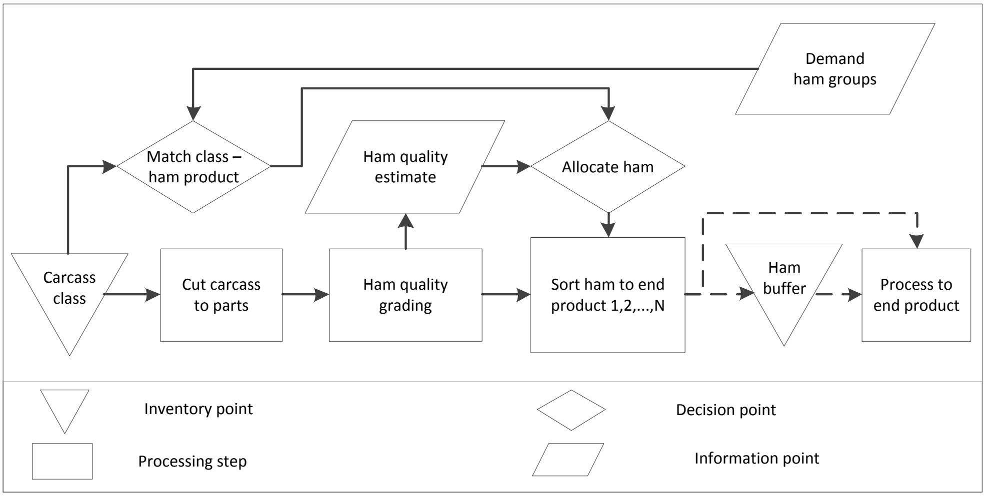

Figure 2.1: Schematic overview of current processing chain.

are measured and used for product sorting, these being weight and the fat layer thickness at two places. Other ham quality features related to the quality of meat are difficult to determine under commercial slaughterhouse conditions, and are currently not used for product sorting. These quality features do, however, affect the sensory appearance, shelf life and processing characteristics of meat products [Rosenvold and Andersen, 2003]. In this case study, we assess the use of NIRS-estimates of WHC in sorting for advanced product quality features.

After a ham is allocated to an end-product group, it is processed by a number of processing steps that make this ham specific to the order (e.g. remove tail, remove tailbone, and trim fat). A ham is processed either directly at the processing stations (multiple ham products will be processed at the same time), or after temporary storage. In case of temporary storage, the hams are loaded to special storage hooks, which involve manual labour. After temporary storage, the groups of sorted hams are processed group by group (serial processing). In a processing setup without use of buffers, multiple ham end products are processed at the same time (parallel processing). Parallel processing of end products might result in a lower processing efficiency, since processing stations might not be used to full capacity. When processing buffers are used, a delay between the start of ham sorting and processing is set by the decision-maker. Buffering of hams is undesirable, due to the perishable nature of meat products, where product buffering may reduce the microbiological quality [Raab et al., 2008], and it might result in product weight losses due to shrinkage [Huff-Lonergan and Lonergan, 2005]. The decision-maker, therefore, wants to finish sorting hams of a carcass class before processing starts, while minimising the total delay to reduce the meat weight losses. The minimum time between the start of carcass sorting and ham processing is, therefore, determined by the time required to sort all parts within the largest carcass class. After the specific processing, steps belonging to the end products have been performed; the processed ham products are packed and delivered to end customers. Packing and delivery is outside the scope of this case study.

2.3.3 Process redesign scenarios

Based on the literature review, insights obtained from the current practice and the available infrastructure, the project team decided to assess process designs that differ with respect to three variables. First of all, the designs differ in the number of WHC segments to which products are sorted (i.e. the number of WHC classes used). In the current design, there is no sorting for WHC (i.e. 1 segment). In the alternatives, we distinguish sorting to 3 and 5 WHC segments. A maximum of 5 segments was chosen since keeping more than 5 flows separated at the same time is too complex in the current infrastructure. Furthermore, marketing more than 5 WHC segments is expected to be difficult. The second factor that varies in the process design scenarios is the availability of product quality information. The information levels we distinguish are (i) no WHC-information, (ii) WHC estimates with uncertainty, and (iii) perfect WHC-information of a particular ham product. Information levels (i) and (iii) refer, respectively, to the current situation where no WHC-information is available and the ideal situation. Information level (ii) represents the situation where NIRS-based WHC estimates are used. The third factor that is varied is whether hams are temporarily buffered after sorting, or processed directly. Recall that product buffering will result in product weight losses and an additional labour investment, whereas direct processing involves parallel processing of various end products, which might reduce labour efficiency of processing. A schematic overview of the process design scenarios is found in Figure 2.2, where the difference between direct processing and the buffered processing strategy can be observed in the upper and lower parts of the figure, respectively.

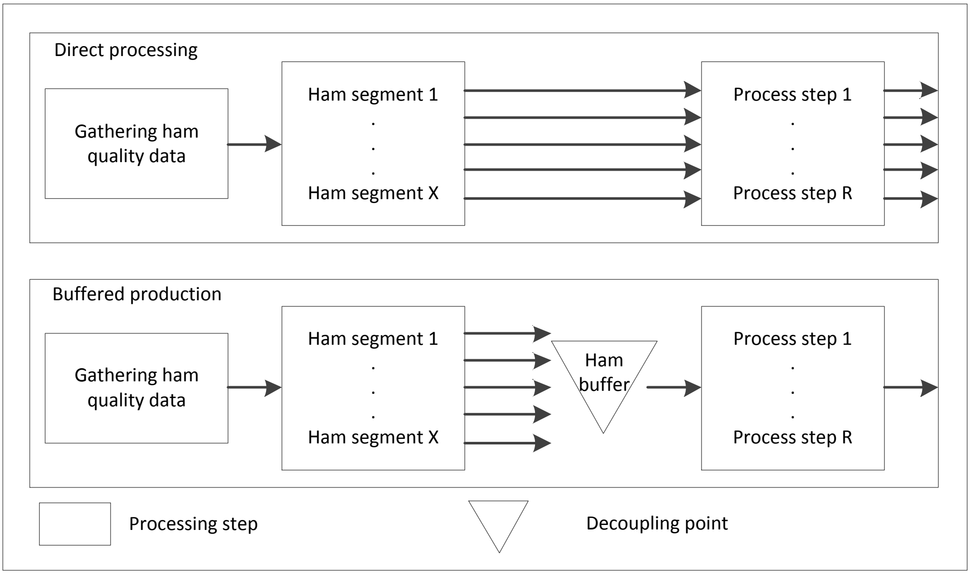

Figure 2.2: Schematic overview of buffered and non-buffered process design scenarios.

Based upon the three design parameters with 3, 3, and 2 alternatives respectively, a total of 18 different process design scenarios can be distinguished. Four process design scenarios are, however, excluded since in the case of only 1 quality segment it is not necessary to consider designs that differ in the availability of product quality information. A summary of the remaining 14 process design scenarios can be found in Table 2.2. To simplify the scenario names, a coding is used, in which the first number indicates the number of segments that is sorted to (1, 3, or 5), the second letter indicates the available product quality information (I = irrelevant, N = no information, E = quality estimates, and P = perfect information), and the third letter indicates the processing strategy (B = buffered, N = non-buffered).

In this overview, the current way of operating is represented by process design scenario 1IN. In that case, no advanced product sorting is used, no advanced product quality information is available, and products are directly processed. The other process design scenarios differ with respect

Table 2.2: Summary of process design scenarios.

Scenario number	Number of segments (1, 3, 5)	Product quality information (I, N, E)	Buffered or non buffered (N, B)
1: 1IN (current)	1	Irrelevant	Non buffered
2: 1IB	1	Irrelevant	Buffered
3: 3NN	3	Not available	Non buffered
4: 3EN	3	Estimates	Non buffered
5: 3PN	3	Perfect	Non buffered
6: 3NB	3	Not available	Buffered
7: 3EB	3	Estimates	Buffered
8: 3PB	3	Perfect	Buffered
9: 5NN	5	Not available	Non buffered
10: 5EN	5	Estimates	Non buffered
11: 5PN	5	Perfect	Non buffered
12: 5NB	5	Not available	Buffered
13: 5EB	5	Estimates	Buffered
14: 5PB	5	Perfect	Buffered

to the sorting complexity (either sorting to 3 or 5 segments), the availability of product quality information, and the use of buffers.

2.3.4 Performance measurement

In collaboration with the industrial partner, and based on common performance indicators found in the literature, four KPIs are defined to assess the performance of process design scenarios. These KPIs relate to (i) labour costs in processing, (ii) costs of ham buffering, (iii) order compliance, and (iv) expected customer claim costs. Customer claim costs, in the form of price discounts, are a common measure in meat supply chains to compensate for deviations to customer specifications. Other common performance indicators in meat chains, such as raw material yield, are influenced at decision levels outside the scope of this research and are omitted from the study. The first performance indicator, labour costs, is driven by labour consumption at the processing stations during the time that each of the processing stations is manned. Measurements showed that on average 2 labour-min are required to open a processing station, and another 5 labour-min for closure of a processing station. Average labour costs of €30 per hour are assumed, and total labour costs are divided by the total weight of all processed carcass parts to present labour costs in €/ton of ham end product. Labour costs related to ham buffering are accounted for in the buffering costs. Labour consumption before product sorting or after processing (e.g. packaging or labelling) is left out of consideration, since this is not affected by differences in process design scenarios.

The second performance indicator, the cost of product buffering, consists of two parts, these being the weight losses during the product buffering period, and the labour required for ham buffering. The average weight loss during buffering is approximated at 0.044% per hour, based on a set of 993 weight loss measurements over a period of 24 h. The standard error of this average weight loss was 0.001015%, which is, approximately, 2.3% of the average weight loss. By multiplying the average weight loss ratio with an average price of meat products (€2.40 per kg), the average costs of weight losses during product buffering is approximated at €1.06 per ton per hour. The total costs of weight losses during buffering are determined by multiplying the weight of individual hams with their residence time in the buffering room and the approximated costs of weight losses per hour. The labour consumption for loading and unloading of hams in process designs with buffered production is determined by multiplying the number of buffered hams with an average labour consumption of 12 s for loading and unloading of carcass parts. Average labour costs of €30 per hour are assumed, and total labour costs are divided by the total weight of processed hams to convert labour costs to €/ton of ham products. The sum of weight loss costs and buffer-labour costs are presented as buffering costs.

The sorting performance is evaluated in two ways: (i) the ratio of products that is incorrectly sorted to an end-product group, and (ii) the expected customer claim costs per ton of product. The first rate is determined by checking the rate of products that do not fulfil the requirements of the end-product group it is assigned to. We assume customer claim costs in the form of price discounts that are proportional to the deviation from customer specifications. Total customer claim costs are determined by multiplying the deviation from customer specifications of hams that are incorrectly sorted with both ham weight and a discount rate of €0.05 per kg per deviation unit. This discount rate is determined in collaboration with company experts based on experience with earlier customer claim costs. By dividing the total claim costs by the total ham weight, we acquire average claim costs per ton product, which is an important indicator for sorting performance.

2.4 Simulation modelling

In Section 2.4.1, the various elements and relationships of the discrete event simulation model are discussed. The input data that are used in the experiments are given in Section 2.4.2, whereas the simulation instance we consider in this chapter is described in Section 2.4.3.

2.4.1 Model elements and relationships

A common approach in quantitative analysis of supply chain designs that include stochastic elements is the use of simulation models. Several simulation approaches can be distinguished, of which discrete event simulation is an appropriate method for tactical and operational decision-making [Kellner et al., 1999, van der Zee and van der Vorst, 2005]. This modelling technique is most widely used in business and manufacturing industries [Jahangirian et al., 2010]. In a review on simulation in supply chains, Terzi and Cavalieri [2004] indicate that discrete-event simulation is a suitable method to evaluate design scenarios, since (i) companies can perform a what-if analysis prior to taking a decision, (ii) various design scenarios can be compared without interrupting the real system, and (iii) it permits time compression so that timely policy decisions can be made. In what follows we, therefore, propose a discrete event simulation model. The model is implemented using the Stochastic Simulation in Java toolbox (http://www.iro.umontreal.ca/~simardr/ssj/indexe.html).

The moving items in the simulation model we consider are Carcasses and Hams. Each Carcass is sorted to a CarcassClass, which has a set of specifications for carcass quality features. Carcasses are cut into three carcass parts, class by class at a fixed processing rate, and we simulate only the Ham part. Each Ham receives a HamQualityEstimate. Based on the HamQualityEstimate and the set of available HamOrders, each ham is allocated to one of the HamOrders. These HamOrders contain a set of specifications including the CarcassClass the Ham should originate from, the allowed Ham quality specifications, and a list of HamProcesses that have to be performed to fit the HamOrder. After sorting the Ham is either transferred directly to the HamProcessors, or temporarily buffered in the HamBuffer, depending on the process design. At the HamProcessors, the Hams are processed serially at the same rate as carcass cutting. After the last HamProcess has been performed, the Ham is finished, and performance data are gathered.

Process design scenarios in this simulation differ with respect to the number of WHC segments in the HamOrders, the WHC quality information available in the HamQualityEstimate, and the use of a HamBuffer. Prevalence of WHC is simulated by randomly assigning a WHC value to a ham following an empiric prevalence of WHC. This product quality is used as the real WHC. In scenarios where no product quality information is available, products are sorted randomly, unrelated to the real WHC of that product. In scenarios where WHC estimates are available, these estimates are generated based on the real WHC plus a random estimation error, which follows the empirical estimation errors. If perfect WHC information is available, the real WHC is used for product sorting. For performance measurement, the throughput time of Hams between cutting them from the Carcass up to the moment where they are fully processed is monitored. Next to that, we monitor whether the Ham actually fulfils the WHC-specifications of the order it is processed to, and if not, what the deviation from the customer specifications was. These data are used to determine the rate of Hams that does not fulfil order specifications and the customer claim costs, respectively. The labour consumption in processing and buffering is determined by measuring the total time the ham processing units have been opened, and by multiplying the number of buffered hams with the average labour consumption for ham buffering.

2.4.2 Input data

Our industrial partner provided, together with data regarding the relation between quality features of carcasses and hams, a large data set with carcass quality data. The output we present in this chapter is based on a simulation that includes 70,728 carcasses originating from 12 separate carcass quality classes slaughtered in 15 consecutive days. A set of quality specifications for ham end products is available for each of the 12 separate carcass quality classes. After carcass classes are cut into carcass parts, the hams are sorted to 3 main end products each, which can be subdivided into various WHC-segments depending on the process design.

The industrial partner provided a data set containing both the estimated (using the NIRS technology) and the real WHC (determined by measuring the drip loss over a period of 24 h) of samples. The prevalence of different levels of real (measured) drip loss in the available samples can be observed in Figure 2.3. We approximated the standard deviation of the NIRS estimation error at 0.80% based upon the 993 paired samples of both the real (measured) WHC and the predicted WHC. This value is used to generate WHC estimates in scenarios 3EN, 3EB, 5EN, and 5EB. The specifications of the 3 and 5 WHC-segments are chosen to make segments that are roughly equal in size. In the case of sorting to 3 WHC-segments, each segment, therefore, contains about 33% of the hams (lower, middle and upper segments), whereas in the 5 segment case, each segment contains approximately 20% of the hams, in line with market demand.

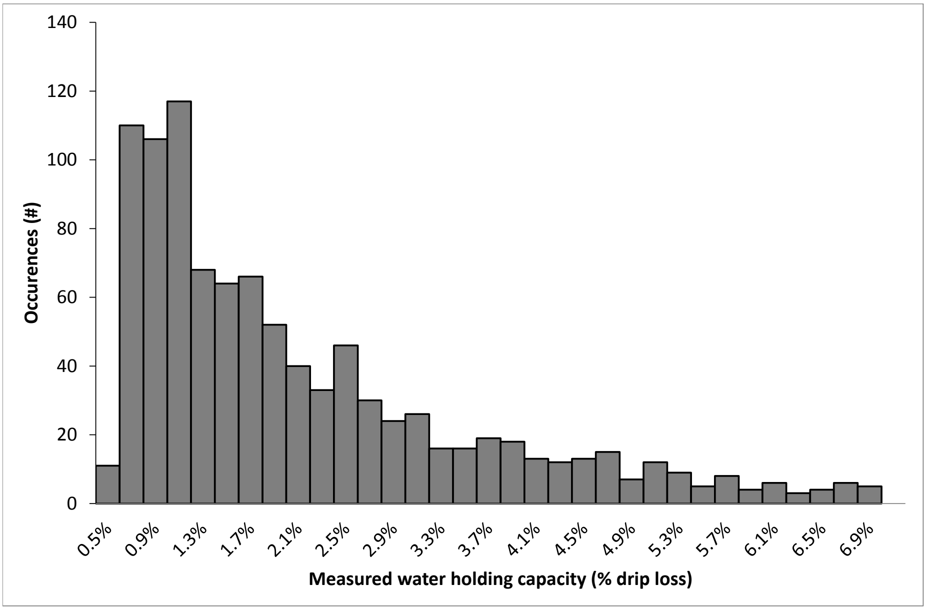

Figure 2.3: Product quality prevalence, based on 993 samples.

2.4.3 Simulation instance

The quality features of individual hams are simulated based on available carcass data and the relation between quality features of whole carcasses and hams. One hundred simulation runs were used to assess each process design scenario, and due to the large number of carcasses in each simulation run, the model outputs showed little variation within these 100 replications. A total of 9 possible ham processing steps are incorporated. To make the labour requirement of the various end-products comparable, we adjusted the various end-product recipes by assigning the same number of processing steps to each of the end products. This results in comparable labour requirements for each end-product group.

In case of non-buffered production (design scenarios 1IN, 3NN, 3EN, 3PN, 5NN, 5EN, and 5PN), carcasses that are cut are directly processed at the processing line, resulting in a short throughput-time. In case of buffered production, a period of 1.5 h was used between the start of carcass cutting and the processing of sorted hams. This ensured that all hams from a carcass class were sorted before processing starts, while the increase in throughput-time caused by buffering is minimal.

2.5 Results

This section presents the results of the analysis of the process designs in Section 2.5.1. Section 2.5.2 then gives more insight into the sensitivity of model outputs to changes in sensor information accuracy.

2.5.1 Scenario analysis

The developed simulation model allows for a detailed analysis of the performance of all process design scenarios. In this case study, we limit the output to the KPIs discussed before; the aggregated performance data can be found in Table 2.3 and Figure 2.4. To simplify interpretation of the results, the properties of the process design scenarios are also given in Table 2.3. All costs in this section are given in €per ton of product. The average daily throughput was 61.3 ton of hams per day, which, with an average value of €2.40 per kg, represents a value of approximately €147.000 per day. A cost-reduction of €5.00 per ton, therefore, represents a saving of 0.21%, or €307 per day. Since profit margins are typically below 1% in this industry [PVV], this is a significant improvement.

Table 2.3: Performance of process design scenarios.

Scenario number	Segments (1,3,5)	WHC information (I,N,E,P)	Buffer (N,B)	Out of customer specifications (%)	Claim costs (€/ton)	Labour costs (€/ton)	Buffering costs (€/ton)	Overall costs (€/ton)
1: 1IN (current)	1	Irrelevant	No	0.0	0.00	16.00	0.00	16.00
2: 1IB	1	Irrelevant	yes	0.0	0.00	11.50	8.52	20.02
3: 3NN	3	Not available	no	65.8	61.76	28.84	0.00	90.60
4: 3EN	3	Estimates	no	32.9	16.71	28.86	0.00	45.57
5: 3PN	3	Perfect	no	0.0	0.00	28.81	0.00	28.81
6: 3NB	3	Not available	yes	65.9	61.85	15.47	8.52	85.84
7: 3EB	3	Estimates	yes	32.9	16.65	15.55	8.52	40.72
8: 3PB	3	Perfect	yes	0.0	0.00	15.47	8.52	23.99
9: 5NN	5	Not available	no	79.3	76.68	28.82	0.00	105.50
10: 5EN	5	Estimates	no	51.0	26.19	28.82	0.00	55.01
11: 5PN	5	Perfect	no	0.0	0.00	28.83	0.00	28.83
12: 5NB	5	Not available	yes	79.3	76.53	16.82	8.52	101.87
13: 5EB	5	Estimates	yes	51.0	26.25	16.51	8.52	51.28
14: 5PB	5	Perfect	yes	0.0	0.00	16.88	8.52	25.40

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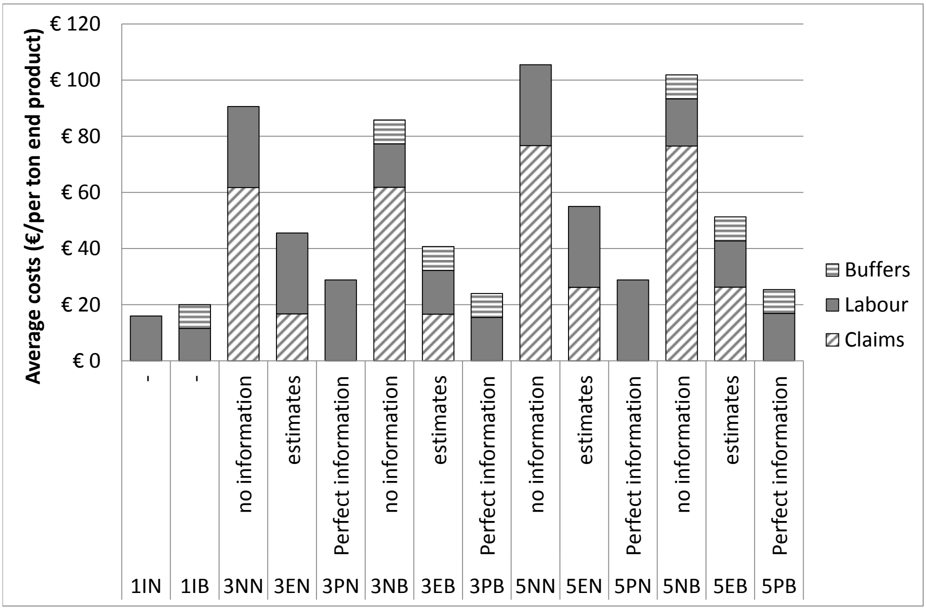

Figure 2.4: Performance of process redesign scenarios.

As mentioned in Section 2.3.3, the process design scenarios differ in (i) the number of WHC segments that is sorted to, (ii) the available product quality information, and (iii) whether the sorted hams are directly processed or temporarily buffered. The rate of products that does not fulfil customer specifications, and the expected claim costs, and costs for labour and product buffering are given in Table 2.3 and Figure 2.4. Please note that the costs for investments in sensor equipment are not included in this overview. Furthermore, the additional value that can be obtained by advanced product segments is not included. To make sorting to advanced product segments economically feasible, the increase of costs due to segmentation should at least be compensated by the added value of advanced quality segments.

The results in Figure 2.4 and Table 2.3 reveal that use of WHC estimates in sorting to 3 or 5 segments will reduce expected claim costs compared to the current situation (no WHC information) by 73% and 66%, respectively.

This shows that, despite uncertainty in WHC estimates, use of NIRS dramatically reduces expected customer claim costs. The output also reveals that the average deviation from customer specifications for incorrectly sorted products is smaller when WHC estimates are used, since the relative reduction of customer claim costs is stronger than the reduction of incorrectly sorted hams in the case of WHC estimates. Note that although advanced product sorting results in significant cost increases, these increases are relatively modest compared with the average product value of €2400 per ton.

Table 2.3 and Figure 2.4 also show that increasing sorting complexity in the current process design (with no buffer) by sorting to 3 or 5 WHC segments will increase labour costs by 80% for both cases. If sorting buffers are used (scenario 1IB), the increase in labour costs resulting from sorting to 3 or 5 WHC segments is reduced to 35% and 46%, respectively.

The product buffering costs (€8.52 per ton) do not outweigh the labour cost reduction in the current sorting complexity (€4.50 per ton) for scenarios without sorting for WHC (scenario 1IN versus 1IB). For scenarios with 3 or 5 WHC segments, the use of temporary buffers does reduce overall costs by on average €4.81 and €3.60 per ton, respectively (scenarios 3NN, 3EN, 3PN versus 3NB, 3EB, 3PB, and scenarios 5NN, 5EN, 5PN versus 5NB, 5EB, 5PB).

Table 2.3 also shows the effect of different levels of product quality information on sorting performance. As indicated before, we do not distinguish different levels of availability of quality information in the current scenario, because in this scenario, products are not sorted according to WHC anyway. As expected, 0% of the products are incorrectly sorted if perfect information is available (scenarios 3PN, 3PB, 5PN, 5PB). Furthermore, if no advanced product quality information is available (scenarios 3NN, 3NB, 5NN, 5NB), a high rate of products will not fulfil customer specifications (66% for 3 segments, 79% for 5 segments) and expected customer claim costs will be high (on average €61.80 for 3 segments, and €76.60 for 5 segments). The expected customer claim costs of process design scenarios that use WHC estimates is, compared to sorting without WHC information, reduced by on average 73% for 3 segments, and 66.4% for 5 segments. This would reduce the expected daily customer claim costs by €2766 and €3094 for 3 and 5 segments, respectively (or 1.9% and 2.1% of the total turnover) if compared to a situation where no quality estimates are available. More insight into the sensitivity of both claim costs and the rate of incorrectly sorted hams for changes in sensor accuracy can be found in Section 2.5.2.

2.5.2 Sensitivity to sensor accuracy

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To gain insight into the sensitivity of sorting performance for changes in sensor accuracy and thereby the estimation error, we conducted a sensitivity analysis. Figure 2.5 shows the sensor accuracy, represented by the standard deviation of the estimation error around the real product quality, against the expected customer claim costs. This is done for sorting both to 3 and to 5 WHC segments. The current sensor has an estimation error with a standard deviation of 0.8, and in the experiments the standard deviation of the estimation errors was varied between 0.5 and 1.2.

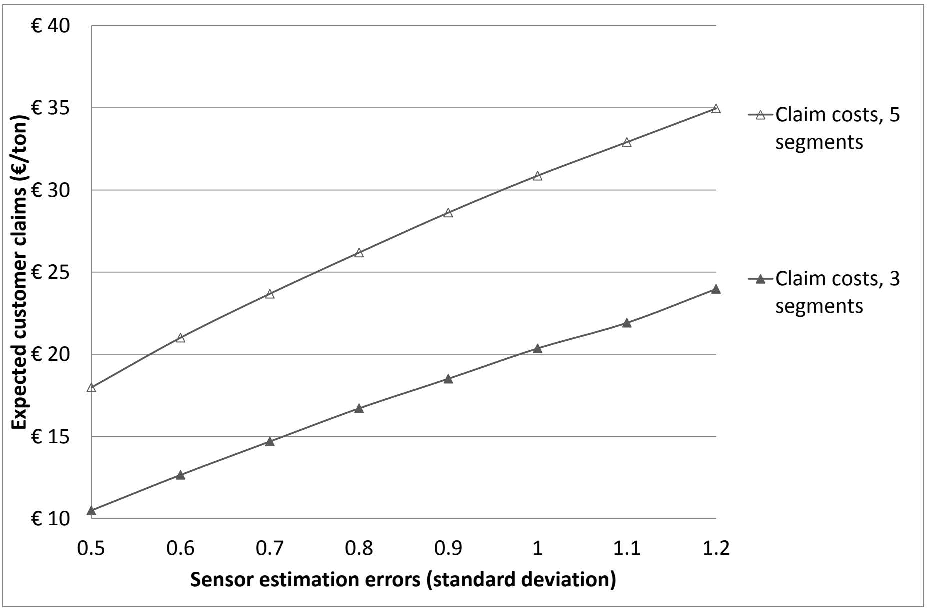

Figure 2.5: Sensitivity analysis of sensor accuracy.

This is expected to be a realistic range for operational sensor accuracy; a higher estimation error than the current best estimate might occur if concessions to sensor accuracy are made to reduce operational costs, whereas future improvements in the NIRS technology might result in a lower estimation error.

Figure 2.5 shows that the expected customer claim costs rise with higher estimation errors. This indicates that if the estimation error is lower, the added value from advanced sorting that is required to make advanced sorting profitable is also reduced. In Figure 2.5, we also observe that the increase in customer claim costs with higher estimation errors is larger if sorting to more segments. The insights obtained from Figure 2.5 can be used to analyse the potential gain from acquiring technology that provides better quality estimates.

2.6 Discussion and conclusion

Consumer demand for food products has become more segmented with respect to product quality features in recent years. This provides opportunities for food processors to add extra value by differentiating product flows. Many food processing companies struggle to differentiate product flows to serve segmented markets, due to specific characteristics of food products (e.g. a divergent production process, homogenous product quality, a multitude of product quality features, and product quality features that are difficult to determine).

Food processors, therefore, need effective mechanisms to differentiate product flows despite complicating factors. Gathering and using product quality information is of key importance for advanced product sorting. To assess the use of product quality information in product sorting at a meat processing company, a model was developed that simulates a ham sorting and processing chain. Fourteen process design scenarios were defined that differ with respect to (i) the number of segments that are sorted to, (ii) the available product quality information, and (iii) whether the sorted hams are directly processed or temporarily buffered. The sorting performance is assessed based on expected customer claim costs, order compliance rate, labour costs, and buffering costs. Based on the results presented in Section 2.5.1, we conclude that use of product quality estimates in product sorting is an effective approach to reduce customer claim costs while sorting products to multiple segments. By simulating sorting performance of scenarios with perfect information, scenarios with no information, and product quality estimates that differ in accuracy (Section 2.6), we provide insight into the advantages/disadvantages of acquiring more/less accurate product quality information in terms of expected claim costs.

The findings reveal that with a low sorting complexity (no sorting for advanced product quality features), the use of production buffers increased the overall costs by 25%. This confirms the claims made by He et al. [2011] that decision-makers should carefully assess the effect of measures to increase flexibility on profitability and efficiency before investing in them. For more complex sorting (into 3 or 5 segments), the use of production buffers resulted in a reduction of overall costs between 3.4% and 16.7%. This suggests that higher processing complexities make use of processing buffers favourable, which confirms the findings of Hallgren and Olhager [2009].

The findings of this case study can be used by practitioners to determine (i) the process design that is most appropriate for a specific sorting complexity, (ii) the extra costs that can be expected if sorting for more product quality features, (iii) the order compliance and customer claim costs that can be expected if sorting with the current accuracy of product quality estimates. Furthermore, the approach presented in this chapter enables practitioners that face segmented customer demand to develop and assess responsive and flexible supply chain configurations. The most appropriate product mix and processing strategy can be determined based on the added value of advanced quality segments. In general, it can be said that a higher sorting complexity makes use of sorting buffers favourable, whereas better quality predictions reduce the expected customer claim costs. Future research is needed to determine consumers willingness to pay for special product segments. This can be used, in combination with model outputs, to determine whether the added consumer value outweighs the investments in sensory equipment and the expected increase in processing costs. Note that advanced product sorting will not yield only premium products; some segments will have a product quality lower than average, resulting in a lower market value.

With this case study, we provide an example of how the use of advanced product quality information affects the design of food processes, an area that has not yet received much attention in the literature. Furthermore, we illustrate the importance of flexibility in segmented food supply chains, and confirm claims by Stevenson and Spring [2007], who stated that there is a limit to the degree to which a supply chain can be flexible whilst meeting demand and operating efficiently. Our results indicate that there is a trade-off between the sorting complexity resulting from use of advanced product quality features and the processing efficiency. An interesting direction for future research would be to assess the effect of sorting for advanced product quality features in other supply chains with high levels of segmentation. Furthermore, it would be interesting to assess how other redesign principles (e.g. mechanisation, postponement, and modularity) affect the performance of food supply chains with high levels of segmentation.

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Chapter 3
Application of stochastic programming to reduce uncertainty in quality-based supply planning of slaughterhouses

In this chapter we study the following research questions:

2A. *Can historical quality delivery data from farmers be used to improve sourcing decisions in food supply chains?*

2B. *How can efficient solutions that provide a trade-offs between different performance indicators be obtained using stochastic optimization?*

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Annals of Operations Research,
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Abstract

To match products of different quality with end market preferences under supply uncertainty, it is crucial to integrate product quality information in logistics decision making. We present a case of this integration in a meat processing company that faces uncertainty in delivered livestock quality. We develop a stochastic programming model that exploits historical product quality delivery data to produce slaughterhouse allocation plans with reduced levels of uncertainty in received livestock quality. The allocation plans generated by this model fulfill demand for multiple quality features at separate slaughterhouses under prescribed service levels while minimizing transportation costs. We test the model on real world problem instances generated from a data set provided by an industrial partner. Results show that historical farmer delivery data can be used to reduce uncertainty in quality of animals to be delivered to slaughterhouses.

Keywords Supply chain, Uncertainty, Food supply chain networks, Stochastic programming, Allocation planning, Quality controlled logistics

3.1 Introduction

According to recent studies [Grunert, 2006, Akkerman et al., 2010], several retail and market segments show growing interest in high-quality, healthy and convenience food. As a result, demand for product quality features has become more segmented and product variety has increased significantly. Segmentation in consumer demand for food can be related to all kinds of quality attributes such as taste or color, ease of use, and production process characteristics (e.g. hygiene standards adopted or sustainability issues) [Brunsø et al., 2013]. By differentiating production strategies and processes to exploit this segmented demand, food processors may create extra value [Grunert, 2006]. To realize this, demand preferences of market segments must be translated into clear product and process specifications for different supply chain actors [Perez et al., 2009, Grunert et al., 2004]. Furthermore, supply chain actors need efficient planning systems to match product quality with variable, market specific demand [Grunow and van der Vorst, 2010].

Recent developments in ICT and sensing technology have improved the means to gather, communicate and process information on product quality [Kumar et al., 2009]. This allows food processors to gather and process more product quality information and, in turn, increases opportunities to direct products to market segments that value their specific product characteristics most [van der Vorst et al., 2011]. However, to capture these opportunities, companies need novel logistics concepts and planning systems that exploit product quality information effectively.

Use of product quality information appears to be important in the meat processing chain due to the large variety in product quality, market segments, and processing options. Differences in farmer production and breeding systems result in variation in quality features such as carcass weight, fat layer thickness, and lean meat percentage [Perez et al., 2009], whereas market segments vary with respect to preferred quality features [Grunert, 2006] (e.g. Japan prefers fat meat, Greece prefers light and lean carcasses). These preferences result in differences in economic value of a carcass in different markets. Since slaughterhouses differ in processing equipment and handling procedures, they also differ in end products they can produce and customer markets they can deliver to. This variation in end products and markets may limit the match between available and demanded product quality features at slaughterhouses, resulting in reduced product yield and poor customer satisfaction.

A process analysis of a large European pork processor revealed that in current operations no information on animal quality features is gathered until animals are slaughtered at the slaughterhouse. The current slaughterhouse supply strategy consists of transporting animals to the nearest slaughterhouse (given capacity constraints) to minimize transportation costs. By doing so, the inherent variation in quality between animals of different farmers, caused by differences in farmer production systems, is not exploited to match demand for product quality features of individual slaughterhouses. Furthermore the company faces large uncertainty in product quality received at their individual slaughterhouses. We argue that, to improve carcass yield and customer satisfaction, one should consider product quality information while allocating livestock to slaughterhouses. Of course, a quality-based allocation strategy implies that livestock batches might be transported over longer distances. This, in turn, could affect transportation costs. The marginal benefit of transporting animals over longer distances to target specific markets should therefore outpace the increase in transportation cost. As the reader may imagine, an advanced planning system is essential to capture these complex trade-offs.

In this chapter opportunities associated with use of product quality information in supply planning of a meat processor are assessed. Based on data supplied by an industrial partner, we investigate how product quality information can be used to improve the match between supply and demand for product quality features at slaughterhouses.

The remainder of this chapter is organized as follows: In Section 3.2 we discuss the embedding of the research question in literature and the research approach followed in this case study. Section 3.3 gives a detailed description of the characteristics of the livestock allocation problem. Section 3.4 presents the formulation of the stochastic programming problem. Section 3.5 describes the numerical experiments with the model. Section 3.6 gives a brief conclusion on the research questions and directions for possible further research.

3.2 Literature on the research question and approach

This section presents a review of relevant literature, both on use of product quality of information in food supply chains and on supply chain models dealing with uncertainty. An extensive literature review by Akkerman et al. [2010] on quantitative operations management approaches and challenges in food distribution concludes that effective use of product quality information in decision making was seen in some recent work, but that it remains a challenging research area. Several examples have been found in literature that incorporate use of product quality information. Van der Vorst et al. [2011] introduce a framework called "*Quality Controlled Logistics*" that specifically addresses use of product quality information in logistics decision making to improve the match between demanded and supplied quality features. Dabbene et al. [2008b] used quality decay models in discrete event simulation to minimize logistics costs while maintaining pre-specified quality levels. Rong et al. [2011] developed a Mixed-Integer Linear Programming (MILP) model to integrate food quality in production and distribution planning using temperature at different supply chain stages as decision variables in a logistical network. Van der Vorst et al. [2009] developed a discrete event simulation software package that incorporates continuous quality decay effects into a simulation toolbox called Aladin™. Most literature contributions in this field, however, fail to incorporate the stochastic nature of variation in product quality [Akkerman et al., 2010]. To address presence of uncertainty in food supply chains, Akkerman et al. [2010] suggest use of hybrid models that combine both mathematical programming with simulation techniques. An interesting contribution based on hybrid modelling was presented by Dabbene et al. in [2008a] and [2008b]. An extensive literature review on quantitative supply chain models dealing with uncertainty presented by Peidro et al. [2009] classified literature contributions in this field based on three characteristics. These are (i) source of uncertainty (demand, process or supply uncertainty), (ii) problem type (operational, tactical, strategic), and (iii) modelling system (analytical, artificial intelligence, simulation, and hybrid models). The livestock allocation problem presented in this chapter deals with supply uncertainty at a tactical/operational level. The review above revealed that very limited research is done on tactical and operational models that incorporate supply uncertainty. Furthermore, the few existing works focus on uncertainty in supplier *capacity*. To the best of our knowledge, no work in supply chain planning has so far investigated uncertainty in supplied product *quality*.

The focus of this case study is on the uncertainty in the quality of the supply of farmers to slaughterhouses. The question is how we can use historical information on the number of animals delivered by a farmer and on the quality features (i.e. fat layer thickness, weight, etc) of each of the delivered animals to support decisions on the allocation decisions of deliveries to slaughterhouses. Several contributions can be found in literature that are based upon hybrid sample-based modelling systems. These contributions do, however, deal with uncertainty with respect to supplied or demanded quantity. To the best of our knowledge, this work is the first in which a sample-based solution method is employed to tackle uncertainty in supplied product quality at a tactical/operational level.

3.3 Problem description

We consider the case of a large European meat processor that owns multiple slaughterhouses. Each day this company buys livestock batches from a large, fixed group of farmers. This livestock is then transported by the company to one of its slaughterhouses. A variety of carcass quality features (e.g. fat layer thickness, weight, etc.) are measured after slaughtering. Carcasses are then sorted into separate quality classes based on these quality features. These quality classes are used as a basis for farmer payments, and to match carcasses with orders to be produced. The company currently allocates animals from farms to slaughterhouses based on minimizing total livestock transportation costs, i.e. allocate from farm to the nearest slaughterhouse given capacity constraints. The motivation of our research is that the decision maker would like to determine to which slaughterhouse individual livestock batches should be allocated to reduce the level of uncertainty in quality at the slaughterhouses.

We begin by describing the supply network. The network comprises of farms that deliver batches of livestock and slaughterhouses that consider a number of carcass quality classes. The number of animals a farmer delivers is known in advance since farmers have to indicate the number of animals they will supply several days before the actual delivery. The processing company has the freedom to process these animals at one of its slaughterhouses, and normal practice is to transport all animals from one farm to a single slaughterhouse, since mixing animals from different farms on a truck is forbidden by current health and safety regulations. Each slaughterhouse has a processing capacity in number of animals it can process each day, and a demand for animals of a specific carcass quality class. This demand is assumed to be known in advance, due to existing contracts and commitments with downstream meat processors and retailers in the chain. The animal transportation costs only depend on the distance. Costs for loading and unloading of livestock, veterinary inspection, etc. are assumed to be similar for all farmers and slaughterhouses, and therefore left out of consideration.

Every animal delivered to the slaughterhouse belongs to a single quality class. For a given delivery, the fraction of animals a farmer delivers in a quality class is unknown beforehand. Collecting quality information on all relevant animal quality features at farm level before animals are transported is not a realistic option with current technologies. This is due to high investment and operational costs of measuring livestock quality features at farm level. We investigate the use of historical farmer quality data in the planning of the livestock allocation to reduce uncertainty in quality. Finding an allocation plan, based on stochastic quality, that fulfils demand with sufficiently high probability while minimizing transportation costs is a problem of optimization under uncertainty. Several approaches exist for modelling and solving problems of optimization under uncertainty [Sahinidis, 2004], of which stochastic programming is a widely adopted method [Birge and Louveaux, 1997]. A recent literature review, however, revealed that this technique has only seen limited application in sourcing decisions [Chai et al., 2013].

3.4 Stochastic programming model

We now introduce a stochastic programming model (SP) for the livestock allocation problem discussed in Section 3.3 and a procedure to produce allocation plans with reduced levels of uncertainty and cost. For a background on concepts underlying this SP model the reader is referred to Ben-Tal et al. [2009] and Birge and Louveaux [1997]. The indices, data, and variables used in this SP model can be found in Table 3.1.

The objective function is the total transportation cost TC associated with a given allocation plan:

$$TC = \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij} a_i d_{ij} \tag{3.1}$$

An allocation plan should fulfill the following constraints

$$\sum_{i=1}^{I} X_{ij} a_i \leq c_j \qquad j = 1, \ldots, J, \tag{3.2}$$

$$\sum_{j=1}^{J} X_{ij} = 1 \qquad i = 1, \ldots, I, \tag{3.3}$$

Table 3.1: Model indices, data and variables used in this chapter.

Indices	
i	farm index, $i = 1, \ldots, I$
j	slaughterhouse index, $j = 1, \ldots, J$
k	quality class index, $k = 1, \ldots, K$
l	historical delivery, $l = 1, \ldots, L$
m	iteration counter used in Algorithm 1
n	scenario number, $n = 1, \ldots, N$
Input data	
a_i	animals delivered by farmer i in number of animals.
d_{ij}	transportation costs from farm i to slaughterhouse j in € per animal
c_j	processing capacity of slaughterhouse j in number of animals
ζ_{ik}	uncertain fraction of animals from farmer i in quality class k, $\sum_k \zeta_{ik} = 1$.
h_{jk}	demand for carcass quality class k at slaughterhouse j in number of animals
α	minimum required service level for fulfilling demand h_{jk}, $\alpha \in [0, 1]$
$\mathbb{Q}_i$	set of observed deliveries for farmer i
$\mathbf{z}_{il}$	fraction vector of delivered quality by farmer i in historical delivery l
ξ_{ikn}	quality delivered by farmer i in quality k under scenario n
Ξ_n	matrix of quality deliveries under scenario n
$\mathbb{S}$	finite subset of possible outcomes of random variable on deliveries all farmers
μ_{ik}	average fraction of quality delivered in quality class k by farmer i
cv_{ik}	coefficient of variation in quality delivered in quality class k by farmer i
Decision variables	
X_{ij}	allocation of animals from farm i to slaughterhouse j, $X_{ij} \in \{0, 1\}$
Y_{jkn}	demand fulfilment at slaughterhouse j for quality class k under scenario n, $Y_{jkn} \in \{0, 1\}$
Derived decision variables	
TC	transportation cost in €
sl	service level, $sl \in [0, 1]$

$$\Pr\left\{\sum_{i=1}^{I} X_{ij}\zeta_{ik}a_i \geq h_{jk}\right\} \geq \alpha \qquad j = 1, \ldots, J, k = 1, \ldots, K. \tag{3.4}$$

The objective function TC in (3.1) is to be minimized. Equation (3.2) ensures that slaughterhouse capacity is not exceeded. Equation (3.3) takes care of the allocation of each animal-batch to a slaughterhouse. The chance constraint in Equation (3.4) guarantees that demand for quality (h_{jk}) is met at required service level α. This requirement can be dependent on the slaughterhouse and quality class, but for our case it is sufficient to assume one uniform requirement α. The probability at the left hand side depends on the stochastic variate that is used to model the uncertain parameter ζ_{ik}.

3

The main question in this research is how the allocation plan can be improved with the available information from the past. This information consists of quality data available from L historical deliveries (with $l = 1, \ldots L$), for each of the I farmers (with $i = 1, \ldots, I$), captured in measured fraction vectors $\mathbf{z}_{il}$. For the model of stochastic fraction vector ζ_{ik} we take the support as the set of observed vectors $\mathbb{Q}_i = \{\mathbf{z}_{il}, l = 1, \ldots, L\}$ for each farmer $i = 1, \ldots, I$ where each element in $\mathbb{Q}_i$ has the same probability of $1/L$ on occurrence. Assuming independence between the farmers defines an outcome space $\mathbb{Q}_1 \times \mathbb{Q}_2 \times \ldots \times \mathbb{Q}_I$ with $N = L^I$ possible outcomes, each with a probability $1/N = (1/L)^I$.

The chance constraint (3.4) can then be expressed exactly by what is called in literature on stochastic programming (e.g. [Birge and Louveaux, 1997], [Klein Haneveld and van der Vlerk, 1999]) scenario-based modeling. Let a binary variable Y_{jkn} express that demand h_{jk} is fulfilled ($Y_{jkn} = 1$) when outcome $n = 1, \ldots, N$ takes place. Let $\Xi_{kn} = (\xi_{1kn}, \xi_{2kn}, \ldots \xi_{Ikn})$ be a matrix of outcome n where column ξ_{ikn} corresponds to fraction vector $\mathbf{z}_{il}$ of outcome n in $\mathbb{Q}_1 \times \mathbb{Q}_2 \times \ldots \times \mathbb{Q}_I$. Then chance constraint (3.4) is equivalent to

$$\sum_{i=1}^{I} X_{ij}\xi_{ikn}a_i \geq Y_{jkn}h_{jk} \qquad j = 1, \ldots, J, k = 1, \ldots, K, n = 1, \ldots, N, \tag{3.5}$$

$$\sum_{n=1}^{N} Y_{jkn} \geq \alpha N \qquad j = 1, \ldots, J, k = 1, \ldots, K, \tag{3.6}$$

As the number N of possible outcomes is, even for relatively small number of farmers I and historical observations L, very large, this MILP model only has a theoretical meaning. However, we are interested in obtaining allocation plans with minimized transportation costs that satisfy chance-constraints according to their threshold α. In scenario-based modeling, it is usual to consider a finite subset $\mathbb{S}$ with a limited number (e.g. $N = 160$) of samples Ξ_n of the possible outcomes of the possible outcomes ξ_{ikn} of random variable $(\zeta_{1k}, \zeta_{2k}, \ldots, \zeta_{Ik})$. The observed service level sl, defined as

$$sl = \min_{j,k} \frac{1}{N} \sum_n Y_{jkn}, \tag{3.7}$$

is only an estimation of the service level of allocation plan X, but fulfils the chance constraint $sl \geq \alpha$.

After optimization of the MILP model with the limited number of N samples in the optimization set $\mathbb{S}$, one can evaluate the actual service level belonging to the resulting allocation plan. We use ˆ to denote variables used for evaluation purposes. We evaluate the actual service level of an allocation plan by estimating $\hat{sl}$ using a large evaluation set $\hat{\mathbb{S}}$ of $\hat{N}$ samples, e.g. $\hat{N} = 5000$. To ensure comparable model solutions, the same optimisation sample set $\mathbb{S}$ and evaluation sample set $\hat{\mathbb{S}}$ are used throughout different variants and scenario comparisons.

To gain insight in the trade-off between uncertainty reduction, expressed as service level $\hat{sl}$, and transportation cost TC we present Algorithm 3.1. In this algorithm we vary α_m in a systematic way for each iteration m, generating allocation plans X_m and measuring the corresponding transportation cost TC_m and observed service level $\hat{sl}_m$. The reached service level sl_m for the optimization sample set $\mathbb{S}$ is used to set a new value for parameter α_{m+1}. It is increased by one sample such that the old plan becomes infeasible and the uncertainty in the new plan is reduced accordingly. Notice that $sl_m \geq \alpha_m$ and many times due to the discrete values of the plan and samples it is larger, i.e. $sl_m > \alpha_m$. The algorithm generates an approximation of the Pareto front that minimizes transportation cost TC and maximizes the observed service level $\hat{sl}$. After filtering out the dominated $TC_m, \hat{sl}_m$ combinations the remaining allocation plans are proposed to the decision maker. This allows the decision maker to make a conscious choice for one of the generated allocation plans X_m.

Set $m = 1, \alpha_1 = .6$ and $N = |\mathbb{S}|$
Solve MILP with α_1, sample set $\mathbb{S}$ generating plan X_1
while X_m feasible plan and $\alpha_m < 1$
    determine $\hat{sl}_m$ of X_m based on samples in $\hat{\mathbb{S}}$
    $\alpha_{m+1} = sl_m + 1/N$ and $m = m + 1$
    if $\alpha_m \leq 1$
        Solve MILP with α_m, sample set $\mathbb{S}$ generating plan X_m

Algorithm 3.1: TC-$\hat{sl}$ (in: sets $\mathbb{S}, \hat{\mathbb{S}}$, problem data, out: $TC, \hat{sl}$ front).

3.5 Numerical experiments

3

3.5.1 Problem instances

We consider a base case of the livestock allocation problem that has a similar size as the problem faced by an industrial partner. The base case concerns the delivery of livestock from $I = 72$ farmers to $J = 5$ slaughterhouses on a specific day. Recall that farmers have communicated the delivery day and batch size in advance. In total the 72 farmers deliver $\sum_{i=1}^{I} a_i = 11446$ animals. Each of the slaughterhouses has a capacity of $c_1 = c_2, \ldots, = c_5 = 2400$ animals, resulting in a total overcapacity of 4.8 %. At each of the five slaughterhouses we consider the three most important quality classes (k = 1,2,3). In the dataset these represent 67.6 % of all delivered animals in past deliveries.

The number of historical observations supplied by the industrial partner is $L = 45$ for each farmer. Specifically, historical quality data ($\mathbf{z}_{il}$) is derived from a dataset on quality features of 526105 animals delivered by the 72 farmers in 45 past deliveries. Livestock transportation costs d_{ij} were estimated by multiplying road distances from farm i to slaughterhouse j with fixed livestock road transportation costs of 0.005638 € per animal per km based on estimated truck costs of 0.264 € per km for fuel, driver (0.3125 €), and truck(0.10 €), and an average load of 120 animals. The resulting costs ranges between 0.133 € and 4.33 € for transport of one animal from a farm to a slaughterhouse.

The scenario-based MILP model has been implemented in Xpress Mosel, where the number of scenarios is taken as $N = 160$ randomly drawn samples from the outcome space. The MILP model was then fed to the solver Xpress-MP version 22.01.04 run on an Intel i7 860 CPU with 2.80 GHz and

Table 3.2: Parameter settings in base case model.

Parameter	Value	Definition
I	72	Number of farmers supplying livestock
J	5	Number of slaughterhouses receiving livestock
K	3	Number of quality classes
L	45	Number of observations for each farmer
d_{ij}	0.133 to 4.33	Livestock transportation costs in € per animal
N	160	Number of samples in optimization set $\mathbb{S}$
$\widehat{N}$	5000	Number of samples in evaluation set $\hat{\mathbb{S}}$
α_1	0.6	Initial service level in Algorithm 3.1

4 GB of RAM. A common time-limit of three hours was imposed on the solution time of all instances. The reached service levels $\hat{sl}$ of the found solution were measured using the same set $\hat{\mathbb{S}}$ of $\widehat{N} = 5000$ randomly drawn samples. A summary of the main parameters in the allocation problem we consider can be found in Table 3.2.

3.5.2 Model behaviour of the base case

The current supply strategy of the industrial partner consists of shipping animals from farms to the nearest slaughterhouse (given capacity constraints) in order to minimize transportation cost TC. We first analyse the impact of the current supply strategy (which supplies livestock without using quality information) on the observed service level for a specific quality class. To investigate this, the allocation model is run without constraining demand for specific quality classes, i.e. $h_{jk} = 0$. The resulting minimum cost allocation plan has an objective function value of 7636.22 €. We determine, for this allocation plan, the minimum number of animals delivered to each slaughterhouse from each quality class over the 45 available deliveries. Then, we set the target demand to 120%, 140%, and 160% of this minimum value, respectively; and we assess the service level of the original allocation plan for different slaughterhouse in each quality class for the 45 historical deliveries. The resulting aggregated service level for quality class $k = 2$ at all 5 slaughterhouses is given in Figure 3.1.

These results suggest that, by simply minimizing transportation cost, there is large uncertainty in the number of animals that will be received in a quality class at each of the slaughterhouses. Furthermore notice that there are large differences in the observed service level between the slaughter-

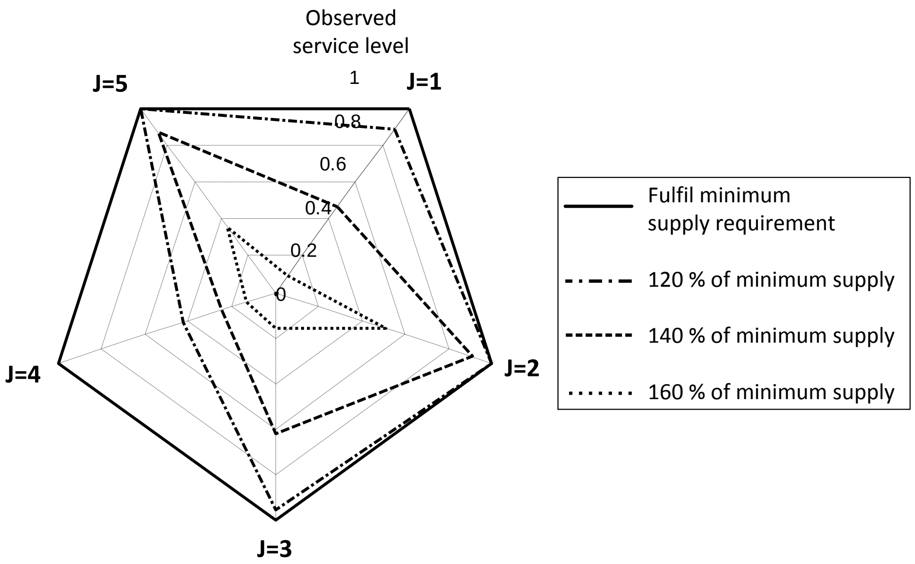

Figure 3.1: Observed service level of quality class $k = 2$ demand at slaughterhouse $j = 1$ to 5 for the minimum transportation cost plan.

houses when demand increases uniformly. This is caused by the case specific locations of farms and slaughterhouses, where most spare capacity is available at slaughterhouses at less favourable locations. Similar figures can be produced for quality class 1 and 3. These findings motivate the use of the decision support SP model.

3.5.3 Trade-off between uncertainty reduction and transportation cost

To assess the effect of the quality based allocation model on transportation cost TC we design an experiment where the demand for quality class k =1 at slaughterhouse $j = 1$ is restricted while leaving demand for other quality classes and slaughterhouses unconstrained. The demand h_{11} is varied between 230 and 260, whereas demand constraints for other combinations of slaughterhouses and quality classes are relaxed, i.e. $h_{jk} = 0$. Figure 3.2 gives insight in the trade-offs between demand variations in h_{11}, observed service level $\hat{sl}$ and transportation cost TC. This graph shows the results

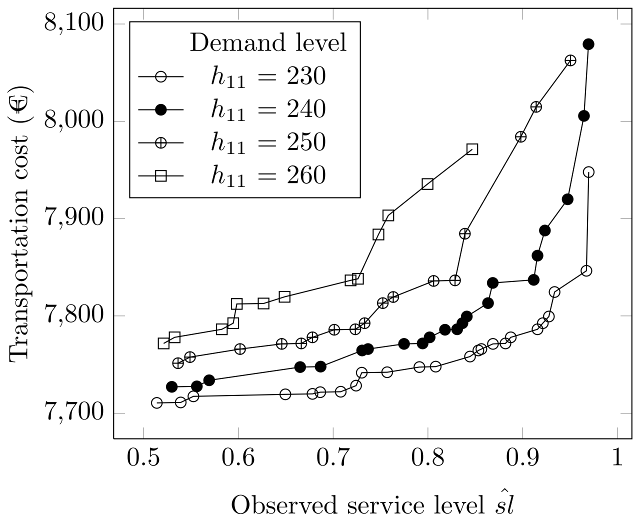

Figure 3.2: Minimum transportation cost fulfilling demand h_{11} at service level $\hat{sl}$.

for varying one specific demand at one of the slaughterhouses. Varying the demand for other quality classes at other slaughterhouses provides a similar graph. Results such as the data in Figure 3.2 can be employed by supply planners to find allocation plans that fulfill orders for specific quality features with sufficiently high probability $\hat{sl}$ while guaranteeing low TC.

3.5.4 Analysis on supplier variance

To study the effect of the quality variance in ζ, we analyse the effect of changes in the coefficient of variation cv of the quality that farmers deliver on the transportation cost TC of the allocation plan. To do so, the average fraction $\mu_{ik} = E(\zeta_{ik})$ of animals each farmer i delivers in a given quality class k is kept constant. Notice that $\mu_{ik} = \sum_{l=1}^{L} \mathbf{z}_{ilk}/L \quad i = 1, \ldots, I, k = 1, \ldots, K$. Now the coefficient of variation $cv_{ik} = \sigma_{ik}/\mu_{ik}$ is varied simulating lower or higher variation than in the observation set $\mathbb{Q}_i$. Figure 3.3 shows the resulting minimum transportation cost TC when multiplying the original coefficient of variation by 0.2, 0.4, 0.6, 0.8, and 1 for each of the farmers at a constant demand ($h_{33} = 650$). Demand constraints for other combinations of slaughterhouse and quality class are relaxed, i.e. $h_{jk} = 0$. Fixing other demand h_{jk} provides a similar graph.

The findings presented in Figure 3.3 suggest that, if a high service level

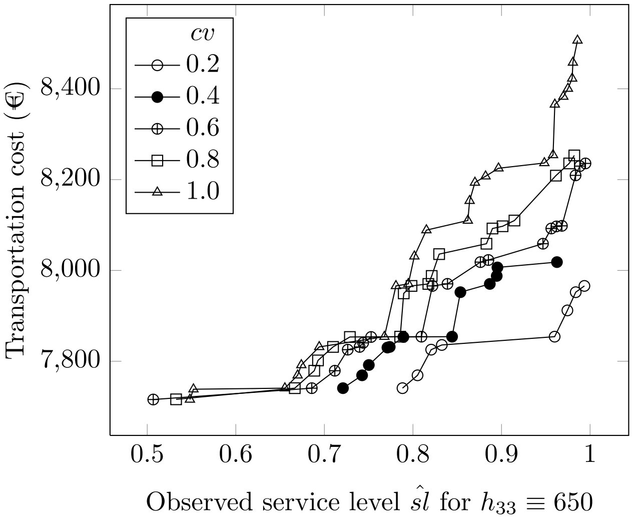

Figure 3.3: Effect of supply quality variance cv on transportation cost.

is required, a more constant quality supply reduces transportation cost TC needed to allocate livestock batches based on quality information. This can be explained by the reduction in supply planning uncertainty due to a more constant delivery of product quality, which reduces the need for hedging to uncertainty. Therefore if achieving a high service level is of key importance, it may be profitable to set up incentive mechanisms to motivate farmers to deliver a more constant quality. The maximum premium that can be paid to reduce the coefficient of farmer variation can be derived from model output similar to that in Figure 3.3.

3.6 Conclusions and further research

For the issue of integrating quality information in logistics decision making, we study a case in meat processing industry. The question is how to generate slaughterhouse allocation plans with reduced levels of uncertainty in product quality received at individual slaughterhouses. To address this research question, a stochastic programming model has been developed that exploits historical farmer delivery data using a scenario-based approach. The computational experience demonstrates the benefits of a quality-based supply planning compared to the current practice of shipping animals to the closest slaughterhouse to minimize transportation costs.

This study shows that historical farmer delivery data can be used to reduce uncertainty in quality of animals a slaughterhouse will receive in future deliveries. The current model therefore helps to reduce uncertainty in supplied quality, and provides insight in the required transportation costs needed to fulfill demand for specific product quality classes. Future works may investigate more accurate and structured reliability measures, such as those discussed in Tarim et al. [2009], in place of the chance constraints discussed in the current model. Another interesting strategy might be to penalize shortages, following Rossi et al. [2012]. The model is currently positioned at an operational/tactical level. The flexible model setup, however, makes it easy to adjust the current set of constraints to make the model more suitable for operational or strategic decision making.

An interesting finding of this study was obtained from the analysis of the effects of farmer variation in product quality on transportation costs of the quality-based allocation strategy. This value gives insight in the benefits processing companies might obtain if farmers deliver a more constant product quality.

The effectiveness of the presented strategy depends on the variability in raw material quality delivered by farmers and the sensitivity of end products and processors to these quality differences. Similar strategies might be applied in other meat chains as well, given that sufficient recent farmer delivery data is available and seasonal variation in quality is limited or predictable. Furthermore, a direct trading relation between farmers and meat processors is required; buying livestock via livestock traders is not likely to yield stable and predictable livestock quality. Similar methods might be applied in sourcing decisions in other food supply chains as well, for instance by using historical data on product ripeness or microbiological quality. Future research could investigate applications such as these to counter problems caused by uncertainty in supplied product quality.

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Chapter 4

Bi-criterion procedures to support logistics decision making: cost and uncertainty

In this chapter we study the following research questions:

2A. *Can historical quality delivery data from farmers be used to improve sourcing decisions in food supply chains?*

2B. *How can efficient solutions that provide a trade-offs between different performance indicators be obtained using stochastic optimization?*

This chapter is based on an article submitted to a scientific journal:

Rijpkema, W.A., Hendrix, E.M.T., Rossi, R.

Abstract

In decision making problems one would frequently like to find solutions that balance multiple objectives. In this study we focus on generating efficient solutions for optimization problems with two objectives and a large but finite number of feasible solutions. Two classical approaches exist, being the constraint method and the weighting method, for which a specific implementation is required for this problem class. This chapter elaborates these specific implementations and applies it to a practical allocation problem, in which transportation cost and risk of shortage in supplied livestock quality need to be balanced. The variability in delivered quality is modelled using a scenario-based model that exploits historical farmer quality delivery data. The performance of both implementations is tested on this specific case, providing insight in i.) the obtained solutions, ii.) their computational efficiency. Our results indicate how efficient trade-offs in bi-criterion problems can be found in practical problems.

Keywords Multi-objective optimization, Allocation problems, Scenario-based modelling, Constraint method, Weighting method, Stochastic programming

4.1 Problem description

In the optimization of business and logistics processes one is frequently faced with conflicting objectives. Specifically, in the meat processing chain, we are not only dealing with logistics costs, but also with large variety in product quality, market segments, and processing options. Differences in farmer production and breeding systems result in variation in quality features such as carcass weight, fat layer thickness, and lean meat percentage [Perez et al., 2009], whereas market segments vary with respect to preferred quality features [Grunert, 2006] (e.g. Japan prefers fat meat, Greece prefers light and lean carcasses). Rijpkema et al. [to appear] describe an allocation problem where a decision maker is confronted with variability in delivered quality. For this problem, a model is presented where one of the objectives is to minimize the expected shortage with respect to a demanded product quality, whereas the other objective is the minimization of transportation cost. The structure of the model implies a bi-criterion model with a finite, but large number of decision alternatives. In so-called bi-criterion problems, the set of non-dominated solutions presents the optimal trade-offs between both objectives, and is called the Pareto set or trade-off curve. These non-dominated solution sets are typically known to be quasiconcave in their objectives, i.e. there is a diminishing marginal rate of substitution between both objectives, see Geoffrion [1967].

There are basically three approaches to find non-dominated solutions for this problem type, being i.) the multiobjective simplex method, ii.) the constraint method, and iii.) the weighting method [Romero and Rehman, 2003]. As the applicability of the multiobjective simplex method is limited to very small-sized problems, its practical usefulness is restricted [Romero and Rehman, 2003]. We therefore do not consider this method here. In the constraint method, first introduced by Marglin [1967], non-dominated solutions are obtained by optimizing a single objective while restricting the other. In the weighting method, first introduced by Zadeh [1963], non-dominated solutions are obtained by optimizing multiple objectives simultaneously (e.g. [Lofti et al., 2011]). The weighting method will find extreme efficient points [Romero and Rehman, 2003], sometimes called supported efficient solutions Hansen [1979]. The constraint method may also find so-called interior efficient points.

The bi-criterion planning problem under consideration has a specific characteristic: the number of feasible solutions is large but finite. The corresponding research question is: how to generate sets of solutions that represent the efficient trade-off between two objectives for this type of bi-criterion problem? To find efficient solutions for this problem type we present two procedures. The first is based on the constraint method and iteratively changes which objective is constrained and which objective is optimized. A similar approach for integer problems has been investigated in Chalmet et al. [1986]. The second procedure is based on the weighting method, using a systematic iterative procedure to vary the adopted weight. The procedure is similar to the approach presented by Cohon et al. [1979]. For a comparison of other procedures on a practical case, we refer to Tóth et al. [2006]. The effectiveness of the two procedures is showcased by the practical allocation problem and differences in computational efficiency and obtained solution sets are discussed.

This chapter is organised as follows. In Section 4.2, a practical bi-criterion problem that has the typical characteristics we are interested in is presented. Section 4.3 introduces the two procedures to generate sets of efficient solutions for this problem type. They are elaborated with instances of the practical case in Section 4.4. Section 4.5 summarizes the findings.

4.2 A livestock allocation model

The type of problem we study in this chapter has a large but finite number of feasible solutions and two conflicting objectives for a single stakeholder. The practical case we are interested in concerns an allocation problem faced by a large meat processing company. For this planning problem, Rijpkema et al. [to appear] present a stochastic programming model to reduce service level violations in supplied livestock quality. In this chapter we do not consider service levels, but instead focus on minimizing the expected shortfall from demanded quality. The adopted model indices, data, and variables used in this allocation model can be found in Table 4.1.

A meat processing company allocates livestock batches from I farms (with $i = 1, \ldots, I$) to J slaughterhouses (with $j = 1, \ldots, J$) and tries to limit logistics cost f_1 of allocation plan X, determined by

$$f_1(X) = \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij} a_i d_{ij}, \tag{4.1}$$

subject to

$$\sum_{i=1}^{I} X_{ij} a_i \leq c_j \qquad j = 1, \ldots, J, \tag{4.2}$$

$$\sum_{j=1}^{J} X_{ij} = 1 \qquad i = 1, \ldots, I, \tag{4.3}$$

$$X_{ij} \in \{0, 1\} \qquad i = 1, \ldots, I, j = 1, \ldots, J. \tag{4.4}$$

Equation 4.2 sets a limit on slaughterhouse capacity, and Equation 4.3 and 4.4 ensure that each livestock batch is allocated to a single slaughterhouse.

In the practical problem, the meat processor distinguishes 12 carcass quality classes. For the elaboration of the procedures, we consider only the demand for a single carcass quality class at slaughterhouse j, and we use h_j to denote the number of demanded carcasses in this quality class at slaughterhouse j. The meat processor would like to ensure that demand for this quality class is fulfilled. However, the fraction of animals that individual farmer i delivers in the specific quality class reveals a certain variability, which we denote by random variable ζ_i. We define $S_j(X)$ as the expected shortfall from demand h_j at slaughterhouse j given allocation plan X, with

$$S_j(X) = E_\zeta[(h_j - \sum_{i=1}^{I} X_{ij} \zeta_i a_i)^+]. \tag{4.5}$$

The decision maker would like to limit both logistics cost f_1 and the sum of the expected shortfall $S_j(X)$ from demand h_j at all J locations. The expected shortfall $S_j(X)$ is based on modelling possible outcomes of uncertain fraction ζ_i using historical farmer delivery data. This historical information consists of quality data available from L previous deliveries, for each of the I farmers. For the model of stochastic fraction ζ_i the support is the set of observed fractions, where each element has the same probability of $1/L$ on occurrence. Assuming independence between the farmers defines an outcome space with $N = L^I$ possible outcomes ξ_{in}, where ξ_{in} denotes the fraction of animals farmer i delivers in the quality class under scenario n. Each of these possible outcomes has a probability $1/N = (1/L)^I$. Using this stochastic model, the expected shortfall $S_j(X)$ is defined by

$$S_j(X) = \frac{\sum_{n=1}^{N} (h_j - \sum_{i=1}^{I} X_{ij} \xi_{in} a_i)^+}{N}. \tag{4.6}$$

The decision maker would like to find an allocation plan X with a limited total expected shortage f_2 at all J slaughterhouses, defined by

$$f_2(X) = \sum_{j=1}^{J} S_j(X). \tag{4.7}$$

As the number of possible outcomes N is, even for relatively small number of farmers I and historical observations L, very large, this MILP model only has a theoretical meaning. In scenario-based modeling (see e.g. Birge and Louveaux [1997]) it is usual to consider a finite subset with a limited number (e.g. $N = 5000$) of samples $\Xi_n = (\xi_{1n}, \xi_{2n}, \ldots, \xi_{In})$ of the possible outcomes of the random variable. This allows us to approximate the performance of solution X in objective f_2.

We now have a scenario-based allocation model that has two objectives ($f_1(X)$ and $f_2(X)$) and a large but finite number of feasible solutions X in the allocation problem defined by Equations 4.2, 4.3, and 4.4. As the reader may imagine, there is a trade-off between the logistic cost (f_1) and expected shortfall of demand (f_2). It is therefore important to find solutions that balance levels of both objective f_1 and f_2, for which two procedures are elaborated in Section 4.3.

Table 4.1: Model indices, data and variables of livestock allocation problem.

Indices	
i	farm index, $i = 1, \ldots, I$
j	slaughterhouse index, $j = 1, \ldots, J$
n	scenario-number, $n = 1, \ldots, N$
Data	
a_i	animals delivered by farmer i in number of animals.
d_{ij}	transportation costs from farm i to slaughterhouse j in € per animal
c_j	processing capacity of slaughterhouse j in number of animals
h_j	demand for carcass quality class at slaughterhouse j in number of animals
ζ_i	fraction of animals from farmer i in the quality class
ξ_{in}	fraction of animals from farmer i in the quality class under scenario n
Ξ_n	realisation of farmer fraction deliveries under scenario n
Variables	
X_{ij}	allocation of animals from farm i to slaughterhouse j

4.3 Bi-criterion algorithms

In bi-criterion problems, a decision maker would like to determine the trade-off between two objectives by obtaining a complete overview of solutions that are non-dominated w.r.t. objectives f_1 and f_2. This can be done by generating a subset $\mathbb{X}$ of non-dominated solutions of the finite set of feasible plans. The corresponding objective values $f_1(X), f_2(X)$ for $X \in \mathbb{X}$ form a Pareto front. We present two procedures to efficiently generate a Pareto front for this problem type, i.e. a problem with two objectives and a large but finite number of feasible solutions. Section 4.3.1 presents a strategy based on the constraint method, whereas the procedure presented in Section 4.3.2 is based on the weighting method.

4.3.1 A constraint method procedure

$\varphi_2 = \min\{f_2(X)\}$	*determine lowest value* f_2
$\mathbb{X} = \text{argmin}\{f_1(X), f_2(X) \leq \varphi_2\}$	*determine and store first solution*
$F_1 = \min\{f_1(X)\}$	*determine lowest value* f_1
$\mathbb{X} = \mathbb{X} \cup \text{argmin}\{f_2(X), f_1(X) \leq F_1\}$	*add second solution*
$F_2 = f_2(\mathbb{X})$	*determine value objective* f_2
$\epsilon = \frac{F_2 - \varphi_2}{K}$	*min gap objective* f_2 *between two solutions*
while $F_2 > \varphi_2 + \epsilon$	
$F_1 = \min\{f_1(X), f_2(X) \leq F_2 - \epsilon\}$	*determine Pareto objective value* f_1
$Y = \text{argmin}\{f_2(X), f_1(X) \leq F_1\}, \mathbb{X} = \mathbb{X} \cup Y$	*determine and store new solution*
$F_2 = f_2(Y)$	*determine Pareto value objective* f_2

Algorithm 4.1: in: problem data, K. out: set $\mathbb{X}$ of efficient solutions in $f_1 f_2$.

In this section, a procedure based on the constraint method is presented to find non-dominated solutions X in $f_1 f_2$ for problems with a large but finite number of feasible solutions. In the constraint method, one objective is minimized (e.g. $\min\{f_1(X)\}$) whereas the other objective is restricted (e.g. $f_2(X) \leq F_2 - \epsilon$). By iteratively changing the objective that is constrained and the objective that is minimized, a set of non-dominated solutions is generated. The obtained solutions may include both extreme efficient points and interior efficient points. Algorithm 4.1 describes the procedure to obtain a set $\mathbb{X}$ of solutions X that are non-dominated in $f_1 f_2$. The symbols used in Algorithm 4.1 can be found in Table 4.2. The decision maker needs to set parameter K, which denotes an upper bound to the number of obtained solutions. If a high value for K is used, a large number of non-dominated solutions might be found, which will require a large number of iterations and therefore much computational effort. If, however, a low value for parameter K is used interesting solutions might be missed. As there is a finite number of feasible solutions, there is a certain value of K for which all non-dominated solutions will be found.

Table 4.2: Symbols used in Algorithm 4.1.

Parameter	Definition
K	Upper bound to the number of obtained solutions
φ_2	Lower bound objective value f_2
F_1	Pareto objective value f_1
F_2	Pareto objective value f_2
ϵ	Minimum gap in objective f_2 between two consecutive solutions
Y	Solution that is temporarily stored

4.3.2 A weighting method procedure

Determine $X_1 = \text{argmin}\{f_1(X)\}$ and $X_2 = \text{argmin}\{f_2(X)\}$
$\mathbb{X} = \{X_1, X_2\}$ *store resulting solutions*
Set $k = 2$, $t = 3$, $w_t = \frac{f_1(X_2)-f_1(X_1)}{f_2(X_1)-f_2(X_2)}$
while $k < t$ *current iteration < number of scheduled iterations*
  $k = k + 1$ *increment current iteration counter*
  $X_k = \text{argmin}\{f_1(X) + w_k f_2(X)\}$
  if $X_k \notin \mathbb{X}$ *if new solution is found*
    $X_{LB} = \underset{X \in \mathbb{X}}{\text{argmin}}(f_1(X_k) - f_1(X))$
    $w_{t+1} = \frac{f_1(X_k)-f_1(X_{LB})}{f_2(X_{LB})-f_2(X_k)}$ *new weight w below w_k*
    $X_{UB} = \underset{X \in \mathbb{X}}{\text{argmin}}(f_1(X) - f_1(X_k))$
    $w_{t+2} = \frac{f_1(X_{UB})-f_1(X_k)}{f_2(X_k)-f_2(X_{UB})}$ *new weight w above w_k*
    $t = t + 2$ *increment scheduled iteration counter*
    $\mathbb{X} = \mathbb{X} \cup X_k$ *store new solution*

Algorithm 4.2: in: problem data. out: set $\mathbb{X}$ of extreme efficient solutions in $f_1 f_2$.

This section presents a procedure based on the weighting method to find non-dominated solutions X in $f_1 f_2$ for problems with a large but finite number of feasible solutions. The objective of the weighting method is to simultaneously minimize both f_1 and f_2, that is

$$\min\{f_1(X) + w f_2(X)\}, \tag{4.8}$$

where weight w denotes the number of units of f_1 a decision maker is willing to trade in to reduce the level of f_2 with one unit. Algorithm 4.2 describes a procedure to gather a set $\mathbb{X}$ of solutions X that is non-dominated in $f_1 f_2$. In Algorithm 4.2 we initially minimize objective $f_1(X)$ and $f_2(X)$ separately, and store the obtained solutions as X_1 and X_2. The following step is to determine the value of trade-off w for which X_1 and X_2 have the same objective function value according to

$$w = \frac{f_1(X_2) - f_1(X_1)}{f_2(X_1) - f_2(X_2)}. \tag{4.9}$$

The solution we obtain by using weight w in Equation 4.8 will be either a new one, or it will be a solution we have found before. If we find either X_1 or X_2 we can conclude that solutions X_1 and X_2 are optimal with respect to weight w, and we stop the search for alternative solutions. If a new solution is found, we can conclude that solutions X_1 and X_2 are not optimal for weight w. In that case we store the new solution as X_3, and restart the procedure to assess whether there are values of w corresponding to other extreme efficient points of the Pareto front other than X_1, X_2, and X_3. The procedure in Algorithm 4.2 will find all extreme efficient solutions for positive values of w (i.e. $0 \geq w \geq \infty$). The symbols adopted in Algorithm 4.2 can be found in Table 4.3.

If a decision maker is able to indicate a weight range where an optimal trade-off between objective f_1 and f_2 is expected she may determine X_1 and X_2 using Equation 4.8 with a lower and an upper bound for w instead. This may reduce the required computational effort.

Table 4.3: Symbols used in Algorithm 4.2.

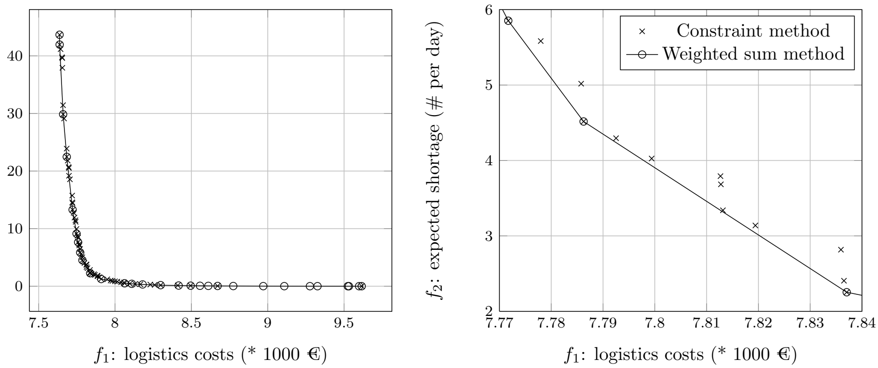
Indices	
k	current iteration counter
t	total iteration counter
Data	
w	maximum allowed increase in objective f_1 to reduce objective f_2 with one unit

4.4 Computational illustration

In this section we illustrate the performance of both procedures presented in Section 4.3 using the livestock allocation problem presented in Section 4.2. The parameter settings used in this allocation problem can be found in Table 4.4. The performance of the solutions generated by both the constraint method procedure (Algorithm 4.1) and the weighting method procedure (Algorithm 4.2) in objective f_1 and f_2 are depicted in Figure 4.1. The complete solution sets are presented in Subfigure 4.1(a), whereas Subfigure 4.1(b) presents a small subset of obtained solutions. The data presented in Figure 4.1 are obtained for demand $h_1 = 250$, whereas a value of $K = 1000$ is used in the constraint method.

Table 4.4: Parameter settings used in computational illustration.

Parameter	Value	Definition
I	72	number of farmers supplying livestock
J	5	number of slaughterhouses receiving livestock
L	45	number of observations for each farmer
N	5000	number of samples in optimization
d_{ij}	0.133 to 4.33	livestock transportation costs in € per animal



(a) Complete set of solutions.

(b) Subset of solutions.

Figure 4.1: Sets of non-dominated solutions obtained using both procedures.

We now vary the demand parameter h_j in order to observe the effect on the set of non-dominated solutions. For clarity of presentation, we only present the solution set obtained using the weighting method procedure in Figure 4.2. A similar set of solutions can be obtained using the contraint method procedure as well. To provide insight in the performance and computational efficiency of both procedures, performance data for both procedures is provided in Table 4.5. In this table we present performance data of solutions obtained using a.) the constraint method procedure with $K = 10$, b.) the constraint method procedure with $K = 1000$, and c.) the weighting method procedure. In Figure 4.1 we observe that, following Romero

Table 4.5: Optimization details for both procedures.

	Constraint method procedure				Weighting method procedure	
	$K = 10$		$K = 1000$			
h_1	# of points	Total time	# of points	Total time	# of points	Total time
210	7	5.21	41	32.07	20	14.58
230	7	6.52	57	62.25	24	30.23
250	9	10.71	69	113.19	29	126.50
270	10	11.96	87	192.26	29	67.08
290	9	14.86	112	348.57	29	67.66

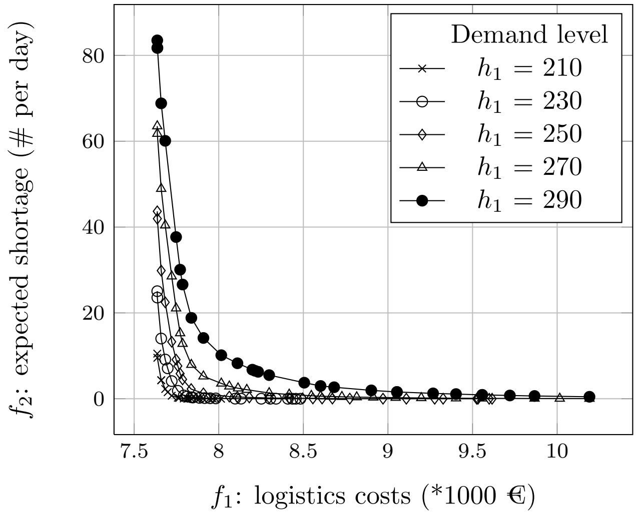


Figure 4.2: Pareto fronts obtained using the weighting method procedure for variations of h_1.

and Rehman [2003], the weight method procedure finds all extreme efficient solutions of the Pareto front, whereas the constraint method procedure may find both extreme efficient and interior efficient solutions. Figure 4.2 can be used by decision makers that want to assess i.) what impact variations in demand level h_j have on both objectives, ii.) the trade-off between logistics cost and expected shortage for each fixed demand level. From Figure 4.1 and Table 4.5 we learn that i.) selecting a low K will improve computational efficiency, but may lead to missing interesting points, particularly in the lower f_2 region, and ii.) selecting a high K will reduce the likelihood of missing non-dominated solutions (ultimately to the point where all non-dominated solutions will be found), but will increase required computational effort. Furthermore we observe from data in Table 4.5 that finding solutions becomes increasingly difficult for higher levels of demand h_j.

4.5 Discussion and conclusion

This chapter presents two practical procedures derived from concepts of multi-criteria decision making to obtain sets of non-dominated solutions problems that have i.) two conflicting objective functions, and ii.) a large but finite number of feasible solutions. The performance and efficiency of both procedures is elaborated for a practical decision making problem where livestock batches need to be allocated to slaughterhouses. In this allocation problem both logistics cost and deviations from demanded livestock quality features are to be minimized. The livestock quality that will be supplied is modelled using a scenario-based approach using historical data on livestock quality delivered by individual farmers. The modelling results indicate that the presented procedures effectively i.) find sets of non-dominated solutions in both objective f_1 and f_2, ii.) provides insight in the trade-off between objective f_1 and f_2.

Acknowledgement

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Chapter 5
Effective sourcing strategies for perishable product supply chains

In this chapter we study research question 3:

How can advanced product quality information be used to improve product sourcing in perishable product supply chains?

This chapter is based on the published journal article:

Rijpkema, W.A., Rossi, R., and van der Vorst, J.G.A.J., International Journal of Physical Distribution & Logistics Management, 2014, Volume 44, Issue 7.

Abstract

This chapter assesses whether an existing sourcing strategy can effectively supply products of appropriate quality with acceptable levels of product waste if applied to an international perishable product supply chain. We also analyse whether the effectiveness of this sourcing strategy can be improved by including costs for expected shelf life losses while generating order policies. The performance of sourcing strategies is examined in a prototype international strawberry supply chain. Appropriate order policies were determined using parameters both with and without costs for expected shelf life losses. Shelf life losses during transport and storage were predicted using microbiological growth models. The performance of the resulting policies was assessed using a hybrid discrete event chain simulation model that includes continuous quality decay. The studys findings reveal that the order policies obtained with standard cost parameters result in poor product quality and large amounts of product waste. Also, including costs for expected shelf life losses in sourcing strategies significantly reduces product waste and improves product quality, although transportation costs rise. The study shows that in perishable product supply chain design a trade-off should be made between transportation costs, shortage costs, inventory costs, product waste, and expected shelf life losses. By presenting a generically applicable methodology for perishable product supply chain design, we contribute to research and practice efforts to reduce food waste. Furthermore, product quality information is included in supply chain network design, a research area that is still in its infancy.

Keywords Perishable Products, Fresh Produce, Supply Chain Design, Sourcing Strategy, Inventory Management, Product Sourcing, Product Quality Information, Food Waste Reduction

5.1 Problem description

In the past decades, food supply chains have become globalised and consumers are demanding year-round availability of fresh products in retail outlets. However, seasonal production means that producers must source products from multiple climate regions throughout the year. Sourcing from each of these regions requires a specifically designed supply chain to supply consumers with fresh products of high quality while minimising overall costs and product waste [Ahumada and Villalobos, 2009, van der Vorst et al., 2009]. Despite efforts to optimize perishable product supply chains, recent research indicates that food waste remains unacceptably high; it is estimated that 40-50 % of all root crops, fruits and vegetables are wasted [Gustavsson et al., 2011]. Food waste can result in hunger, poverty, reduced income generation and reduced economic growth. Food waste is also a waste of production resources such as land, water, energy and other inputs, and affects the sustainability of food production systems [Kaipia et al., 2013].

Poor coordination among supply chain actors, along with inefficient retail practices have been identified as important causes of food waste [Gustavsson et al., 2011]. Recent reports [FAO, 2012] have indicated a need for further assessments that quantify and qualify the scale and value of food waste and identify key constraints, risks and opportunities. Specific strategies that target reduction of food waste must also be developed [Rajurkar and Jain, 2011]. The lack of effective food waste reduction strategies was confirmed by a recent literature review on perishable inventory management by Bakker et al. [2012], which concluded that few literature contributions take dynamic product quality decay into account while sourcing products. This case study adds to literature on this topic by assessing the effectiveness of existing sourcing strategies to perishable product supply chains, and proposing a methodology for waste reduction in international perishable product supply chains. In this chapter we propose the two following hypotheses: (i) existing sourcing strategies may be ineffective at providing appropriate performance in perishable product supply chains; and (ii) robust performance improvements can be achieved in perishable product supply chains by including costs for expected shelf life losses in logistics decision making.

The remainder of this chapter is structured as follows. Section 5.2 provides an overview of the relevant literature areas, before section 5.3 gives an overview of the applied research methodology. Section 5.4 presents the case study that we have used to assess the research methodology, while section 5.5 offers some conclusions, discussion and recommendations for future research.

5.2 Position in literature

In this section, we present the findings of several recent literature reviews in areas relevant to this case study; these are supply chain design (section 5.2.1), sourcing strategies (section 5.2.2), and perishable inventory management (section 5.2.3). Section 5.2.4 discusses the contribution of this case study to the literature.

5.2.1 Supply chain design

In both the academic and business worlds, supply chain management and design have received a great deal of attention. There is a general understanding that the design of a supply chain should be based on the combination of the strategic objectives of the involved organizations and specific characteristics of its supply chain [Simchi-Levi et al., 2007, Slack et al., 2010]. Recent literature reviews [Akkerman et al., 2010, Karaesmen et al., 2011, Rajurkar and Jain, 2011] have recognised that specific characteristics of perishable product supply chains, such as deteriorating product quality and heterogeneous product supply, complicate the design and management of perishable product supply chains. Therefore, design of perishable product supply chains requires modelling efforts, with the aim to satisfy both logistics goals (such as cost and delivery service requirements) and ensure that products are delivered with the right quality at the right place and time [van der Vorst et al., 2011]. The growth in consumer attention towards high-quality food products adds to the need for effective design of perishable product supply chains [Ahumada and Villalobos, 2009]. As a result, it is essential to develop effective supply chain design approaches for perishable products. Several model types can be used to support perishable product supply chain design that often use either simulation or optimization. An example of use of simulation for perishable product supply chain design was that of van der Vorst et al. [2009], who introduced a simulation environment for assessing supply chain configurations in perishable product supply chains. An example of optimization models in perishable product supply chain design was given by Zhang et al. [2003], who minimized supply chain storage and transportation costs while penalizing and constraining product quality decay. For an extended review on supply chain management approaches see Rajurkar and Jain [2011].

5.2.2 Sourcing strategy

An important consideration in supply chain design is the sourcing and purchasing decision; i.e. where to obtain your materials, in what quantities and at what time. The sourcing strategy encompasses a variety of factors, including the number of suppliers that will be contracted, the type of relationship that will be pursued with suppliers, and the type and conditions of contracts that will be negotiated [van Weele, 2009]. Extensive attention, both in practice and in research, has been devoted to topics related to product sourcing, such as intermodal transport, globalization, environmental impact, and multimodality [Kanafani and Morris, 2009]. Choosing the most suitable sourcing strategy depends on the organisations strategic objectives and characteristics, as well as its supply chain. Once a sourcing strategy has been chosen, the actual ordering (i.e. the placement of purchase orders at previously arranged conditions) can take place. The quantity to be ordered is determined using an order policy, which typically attempts to balance performance objectives such as flexibility against shelf availability and cost. Therefore, the sourcing strategy and order policy may enhance product sourcing in perishable product supply chains that struggle with the sourcing of high-quality products. Despite the potential advantages of advanced sourcing strategies and order policies to perishable product supply chains, their use in this area has been very limited; See Shukla and Jharkharia [2013] for an extended review.

5.2.3 Perishable inventory management

Several recent literature reviews on perishable inventory management have concluded that most literature contributions fail to incorporate realistic stochastic and shelf life property features in order policies [Bakker et al., 2012, Shukla and Jharkharia, 2013]. To better represent inventory control in practice, Bakker et al. [2012] recommended a stronger focus on stochastic modelling of deteriorating inventory. A key element in the realistic control of perishable product supply chains is the use of real time product quality information. Despite this, the inclusion of deteriorating product quality in management of perishable supply chains still seems to be in its infancy [Akkerman et al., 2010]. One of the few examples is Blackburn and Scudder [2009], who proposed using temperature-dependent loss of product value for perishable products to determine the economic order quantity in a fresh melon chain. The setting of the present case study, however, is very specific and overlooks variation in quality, and its application is limited to the economic order quantity. Therefore, there is still great potential for sourcing strategies that explicitly use product quality predictions while generating order policies.

5.2.4 Research contribution

As this literature overview shows, integrated product quality influences the design of perishable product supply chains. Despite the impact of quality decay on perishable product supply chains, literature on the use of product quality information in supply chain design, sourcing strategies, and inventory management remains limited. We aim to fill this gap in the literature by presenting a methodology for generating effective sourcing strategies for perishable product supply chains (see section 5.3). In section 5.3, we have assessed the effectiveness of this methodology using an illustrative case study.

5.3 Generating effective sourcing strategies

This section presents a methodology for generating effective sourcing strategies for perishable product supply. Section 5.3.1 provides a short introduction to the required supply chain analysis. A methodology for generating order policies that are sensitive to expected shelf life losses is presented in section 5.3.2. The performance of the generated policies is assessed in section 5.3.3 using a hybrid discretecontinuous event simulation model.

5.3.1 Supply chain analysis

As noted, the sourcing strategy depends on the specific supply chain characteristics. Therefore, to obtain an overview of these characteristics and obtain the data required for quantitative analysis, we first conduct a supply chain analysis. In this analysis all supply chain processes are described and analysed in detail to get a full understanding of their working, and of the dynamics and objectives of the system. After expert interviews, data gathering and data analysis, the sourcing strategy is determined, for which order policies will be generated. We will also define key performance indicators (KPIs) that reflect the performance of the respective processes or supply chain. These KPIs often include common performance indicators (such as transportation cost, storage cost, shortage costs) and case-specific performance indicators (such as product waste, quality discounts) [Aramyan et al., 2007]. For an overview of supply chain analysis methods in perishable product supply chains, see van der Vorst and Beulens [2002].

5.3.2 Order policy generation for perishable product supply chains

There are numerous sourcing strategies available in literature [van Weele, 2009]. In this chapter we adopt a commonly used dual-sourcing policy known as the dual index policy (DIP) [Klosterhalfen et al., 2011]. DIP provides an easily implementable, robust, and often near-optimal solution, which may bring significant savings when the sourcing options differ substantially in lead times [Veeraraghavan and Scheller-Wolf, 2008]. We apply this sourcing policy to a case in which perishable products are sourced from a single location using two alternative transport routes. The regular transport mode is relatively slow but inexpensive, whereas the expedited transport mode is faster but more expensive. Although the DIP is developed for a specific context (sourcing products from two different locations rather than sourcing from a single location using two different transport modes), the modelling assumptions are identical to the case situation as the two suppliers are assumed to differ only in lead time and shipping costs. Therefore, the DIP order policy is applicable.

The DIP order policy uses a regular and an expedited order-up-to position to control product availability at a reasonable cost. These order-up-to positions denote the number of products that will be ordered minus the number of products in stock and the number of products that will arrive within either the regular or the expedited order lead time. Appropriate DIP order policies are determined using demand data combined with cost parameters for product shortages, regular order cost, expedite order cost, and inventory holding cost. To make DIP sensitive to losses in product shelf life, which would improve product quality and reduce product waste, we introduce alternative cost parameters for processes that involve shelf life losses. In the case of DIP alternative, cost parameters are determined by adding costs for expected shelf life losses during expedited transport, regular transport, and inventory holding.

As shelf life reductions reduce the market value of perishable goods

[Wang and Li, 2012], shelf life losses during transport and storage periods can be related to losses in market value. Tsiros and Heilman [2005] found that consumer willingness to pay for products with a low product quality risk (i.e. products that are not commonly associated with food-borne illnesses) decreases linearly as the remaining product shelf life reduces. To the best of our knowledge, there are no sources that indicate how shelf life reductions at the distributorretailer interface affect product market value. Therefore, we have assumed a linear cost increase for losses of shelf life in this part of the supply chain as well. By multiplying the rate of shelf life lost (i.e. the loss in shelf life relative to the total shelf life) by the value of the perishable product, we obtain costs for expected shelf life losses. Shelf life losses are determined using quality prediction models that are described in the following paragraph.

Quality decay of perishable products is often driven by mould or biochemical processes that depend on environmental conditions such as temperature and gas composition. This quality decay can be predicted for a variety of products using data on time and environmental conditions (for example, temperature and/or gas composition) in combination with microbiological growth models [Baranyi, 2010]. Many microbiological growth models, such as that proposed by Hertog et al. [1999], follow a notation comparable to

$$\frac{dN}{dt} = R^M k^s N(\frac{N_{max} - N}{N_{max}}, \tag{5.1}$$

where $\frac{dN}{dt}$ denotes the change in infection level of a spoilage driver over time, R^M is the relative metabolic rate at the specific gas composition and temperature, k^s denotes the growth rate at the specific temperature, N denotes the current infection level, and N_{max} is the maximum achievable infection level (i.e., 1). For normal air, R^M can be set to 1, whereas lower values for R^M can be used for modified atmosphere storage (i.e. storage with altered O_2 and CO_2 concentrations to reduce quality decay). The equations and parameters for determining appropriate values for R^M and k^s are specific for the perishable product at hand.

The infection growth rate at constant environmental conditions, approximated using Equation 5.1, follows a sigmoid curve that ultimately reaches maximum infection level N_{max}. The initial growth of this curve is approximately exponential, slows down as saturation begins, and finally reaches the stage at which all products are infected ($N_{max} = 1$). Since the maximum acceptable infection level at retail outlets is typically low (5 %, following

Hertog et al. [1999]), the exponential approximate in Equation 5.2 is a close approximation of the original sigmoid curve (Equation 5.1).

$$\frac{dN}{dt} = R^M k^s N. \tag{5.2}$$

A key advantage of Equation 5.2 is that the growth rate is independent of the infection level at the beginning of the period. Using this notion, the infection level N_m after m subsequent periods (with $i = 1, \ldots, m$) can be approximated using

$$N_m = N_0 e^{\sum_{i=1}^{m} R_i^M k_i^s t_i}, \tag{5.3}$$

where N_0 denotes the initial infection level, k_i^s and R_i^M denote the growth rate and the relative metabolic rate in period i, and t_i denotes the length of period i. The period t before a product with infection level N_0 reaches infection level N_c at constant environmental conditions is determined using Equation 5.4. This equation can therefore be used to approximate the remaining product shelf life.

$$t = \frac{\ln N_c - \ln N_0}{R^M k^s}. \tag{5.4}$$

Using the notions in Equations 5.3 and 5.4, the rate of shelf life that is lost during consecutive supply chain stages can be approximated based on the initial infection level N_0, the maximum acceptable infection level N_c, and the duration and environmental conditions of the separate stages to which the products are exposed.

5.3.3 Simulation modelling

We assess the effectiveness of the generated DIP in a supply chain context using a simulation model in combination with the process description generated in the supply chain analysis. We employ a hybrid discretecontinuous simulation tool, which includes both discrete features (i.e. individual products moving through a supply chain) and continuous factors (i.e. deteriorating product quality). This tool allows for in-depth analysis of supply chain performance, both for standard KPIs (such as inventory levels, transportation costs, shortages) and case-specific KPIs related to dynamic quality features (such as the remaining shelf life at the moment of delivery). For an elaborate overview of hybrid discretecontinuous simulation models, see Zeigler et al. [2000].

5.4 Case study: International strawberry chain

This section presents a case study of a strawberry supply chain to assess the methodology presented in section 5.3. The structure of this chain is derived from data collected during several company interviews with an international fresh fruit distributor that operates in Belgium. We also obtained company data on a prototype supply chain network for the trade of fresh strawberries from Egypt.

This section is organised as follows. Section 5.4.1 describes the supply chain, before section 5.4.2 outlines the appropriate performance indicators for the supply chain. Section 5.4.3 describes the supply chain scenarios and the generated DIP. Section 5.4.4 describes the simulated system and chain simulation details and section 5.4.5 provides the results of the scenario analysis. Section 5.4.6 provides a sensitivity analysis on several parameters.

5.4.1 Supply chain details

We have considered the case of a Belgian distributor of fresh fruit. The names of the distributor and supplier in the case analysed in this work are

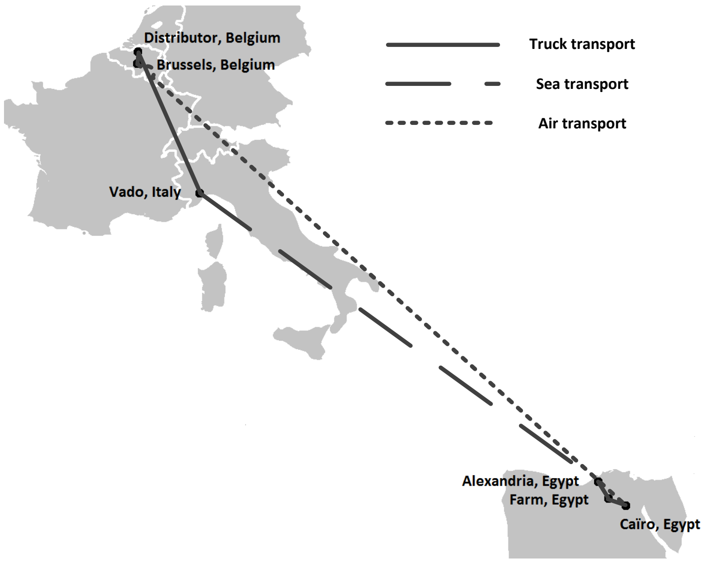

Figure 5.1: Schematic overview of a strawberry supply chain from Egypt to Belgium.

not disclosed, for confidentiality reasons, and we instead use the more generic terms supplier, distributor, and retailer. The distributor imports strawberries from various production regions to provide its customers with fresh strawberries throughout the year. A key problem in international strawberry supply chains is product spoilage and customer complaints, which are mainly caused by a mould called Botrytis cinerea. In this study, the analysis is restricted to the sourcing of strawberries from Egypt, as the distributor does not source strawberries from other regions while strawberries from Egypt are available. We consider a supply chain network that includes a large Egyptian strawberry grower that ships strawberries to the Belgian distributor.

The distributor supplies strawberries to a number of retail outlets that face consumer demand and employs two transport modes to obtain Egyptian strawberries. Figure 5.1 provides a schematic depiction of the strawberry supply chain from Egypt to Belgium. The individual parts of the supply chain are described below. Table 5.1 summarizes the data on the environmental conditions throughout the supply chain.

Farm supply

Strawberries are picked each day between 6.00 a.m. and noon at the straw-

Supply chain conditions	Duration (hours)	Temperature (°C)	σ (°C)
Ambient field conditions	1	15	2
Grower storage room	variable	1	0.25
Distributor storage room	variable	1	0.25
Truck transport to retail outlet	3	2	0.25
Retail outlet	variable	3	0.5
Expedite transport mode			
Truck transport from farm to airport	2	2	0.35
Customs operations	4	10	1.50
Loading, flight and unloading	6	1	0.25
Customs operations + delivery	3	2	0.35
Regular transport mode			
Truck transport from farm to port	4	2	0.35
Customs operations	4	10	1.50
Loading, shipping and unloading	48	1	0.25
Customs operations + delivery	24	2	0.35

Table 5.1: Consecutive steps during regular and expedite transport mode.

berry farm. The Belgian distributor has a special arrangement with its supplier, which promises to deliver day-fresh strawberries; strawberries that are not sold on the same day are sold to regional customers. Based on information provided by the distributor, we assume that the supplier is always able to fulfil the demands of the distributor.

Each strawberry pallet remains on the field, at ambient temperature, for approximately one hour while it is being filled and is then transported to a refrigerated storage room. The average temperature in Cairo between December to February is between 10 and 20 °C, with an average temperature of approximately 15 °C [1]. Based on 5 sigma reasoning, the standard deviation of the ambient temperature is estimated to be 2 °C. Pallets remain in the farmers storage room until a customer order arrives and are then shipped according to the preferred transport route.

Distributor

The distributor orders a number of strawberry punnets every Monday using the regular transport mode, and may order an additional number by expedited transport from Monday to Saturday. The distributor places orders each day at noon, based on regular and expedited order-up-to positions.

[1]Based on data obtained from the World Meteorological Organization

In the regular transport mode, the strawberries are transported by truck from the farmer to the port of Alexandria, Egypt. From Alexandria, the strawberries are shipped to Vado in Italy, where they are loaded on trucks that deliver them to the Belgian distributor. Strawberries that are transported using the expedited transport mode are transported by truck to the airport in Cairo. The strawberries are then flown to an airport in Brussels, from where they are transported to the Belgian distributor by truck. Table 1 summarises the duration and environmental conditions throughout the supply chain. Products that arrive at the distributor are stored in a refrigerated room until retail orders arrive, or until they are thrown away due to spoilage.

Retail demand

The distributor serves a number of retail outlets, each of which places a replenishment order by around midday every day except Sunday. Orders are served by the distributor on a first-come-first-serve basis. Before midday, shop assistants remove spoilt products. Ordered strawberries are delivered to the retailer by truck. The distributor promises that delivered strawberries have an acceptable product quality for at least three days after arrival at the retailer. The retailer distinguishes the three following cases at the moment strawberries are delivered: (i) the product fulfils all retailer quality specifications; (ii) the product is saleable but has less than the desired three days of remaining shelf life, for which claim costs must be paid by the distributor; and (iii) the product is no longer saleable, will be rejected by the retailer, and can be regarded as waste for the distributor. Once the strawberries arrive at the retailer, they are stored in the retail shelves until they are either sold or spoilt. Each of the retail outlets is opened from Monday to Saturday between 8 a.m. and 8 p.m.

5.4.2 Key performance indicators

Based on a number of performance indicators common in sourcing strategies and in collaboration with an industrial partner, six cost-related KPIs have been defined to assess the sourcing performance in this strawberry supply chain. These KPIs are (i) costs of regular transports (C_r); (ii) costs of expedited transports (C_e); (iii) distributor inventory holding costs (C_h); (iv) shortage costs for failing to deliver products (C_p); (v) costs for products that spoil at the distributor (C_w); and (vi) retailer claim costs for products delivered that do not fulfil the minimum required shelf life (C_i). An overview of these cost drivers is given in Table 5.2.

Symbol	Costs €*$punnet^{-1}$	Description
C_r	0.10	Regular transport costs
C_e	0.50	Expedite transport costs
C_h	0.05	Holding costs
C_p	0.50	Penalty costs
C_w	1.00	Cost price wasted strawberries
C_i	see Equation 5.5	Expected customer claim costs

Table 5.2: KPI Parameters.

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The first four KPIs are common cost drivers in inventory management decisions and are based on actual cost for transportation, product holding, and contractual agreements. In this case, we have assumed a constant cost per unit for transportation and inventory holding, without quantity discounts. KPIs (v) and (vi) relate to the product quality of strawberry punnets. The fifth KPI (C_w) represents the cost of products that spoil at the distributor. The retailer claim costs C_i represent the costs the distributor faces if strawberry punnets delivered to retailers have less than the agreed three days of shelf life ($t_{min} = 3$). The remaining shelf life t is determined using Equation 5.4, where N_0 represents the Botrytis cinerea infection level at the moment of delivery and k^s is based on the average storage temperature at the retailer. The resulting retailer claim costs C_i for one punnet are obtained using Equation 5.5.

$$C_i = max(0, C_w \frac{t_{min} - t}{t_{min}}) \qquad (5.5)$$

Equation 5.5 implies that retailer claim costs increase linearly with a decrease of remaining shelf life t, with a maximum of C_w (i.e. the retailer claim equals the product value) and a minimum of 0 (i.e. no premium is paid for products whose shelf life exceeds the minimum requirement).

5.4.3 Generate appropriate policies

As described in section 5.3.2, the gathered supply chain details will be used to generate the appropriate DIP. The first step in this process is to predict shelf life losses during the transport and storage steps. We do so by modelling the growth of Botrytis cinerea using Equations 5.3 and 5.4. The underlying microbiological growth models and parameter values are obtained from Hertog et al. [1999]. Following Hertog et al. [1999], we used

0.798 and 5 % for the initial and maximum acceptable Botrytis cinerea infection level. Shelf life losses during the transport and storage steps are predicted using the growth models presented in section 5.3.2 in combination with the supply chain data presented in Table 5.1. The appropriate DIP was obtained by including costs for these expected shelf life losses in the cost parameters used for generating order policies. Cost parameters generated using these steps are presented for several scenarios in Table 5.3.

These cost parameter scenarios differ in terms of the extent to which costs for shelf life losses are included. This allows us to assess the impact of different scenarios on the different KPIs, as this is not a direct relation (i.e. a higher costs for expected shelf life losses will make use of expedite transport more favourable, resulting in lower average inventory levels, which may result in higher product quality and reduced product waste). These scenarios include 0.00 (i.e. the standard cost parameters), 0.25, 0.50, 0.75, and 1.00 times the cost of expected shelf life losses. The specific values were chosen since the resulting policies cover the complete spectrum from sourcing only by expedited transport in case of product shortages (0.00) to complete sourcing by expedited transport (1.00). The resulting cost parameters that are used to obtain DIP can be found in Table 5.3.

Cost driver	Shortage cost (€$*unit^{-1}$)	Inventory (€$*unit^{-1}*day^{-1}$)	Expedite transport (€$*unit^{-1}$)	Regular transport (€$*unit^{-1}$)
DIP without decay costs	0.500	0.050	0.500	0.100
DIP + 0.25 * decay costs	0.500	0.078	0.523	0.198
DIP + 0.50 * decay costs	0.500	0.105	0.546	0.295
DIP + 0.75 * decay costs	0.500	0.133	0.568	0.393
DIP + 1.00 * decay costs	0.500	0.160	0.591	0.490

Table 5.3: Cost parameters used to determine dual-index policies.

It is computationally infeasible to obtain globally optimal DIP policies for the considered problem size. However, we obtained near-optimal DIPs for these cost parameters using a heuristic procedure proposed by Veeraraghavan and Scheller-Wolf [2008]. These policies were obtained using a set of 50,000 demand observations that were generated following a Poisson distribution with the aggregated average demand of all 10 retail outlets included in the simulation: $\lambda = 6{,}000$ units per day. A Poisson distribution is widely adopted for modelling discrete demand at retail outlets, see Jonsson and Mattsson [2013]. This distribution is particularly appealing in this context because it models purchases as a memory-less stochastic process.

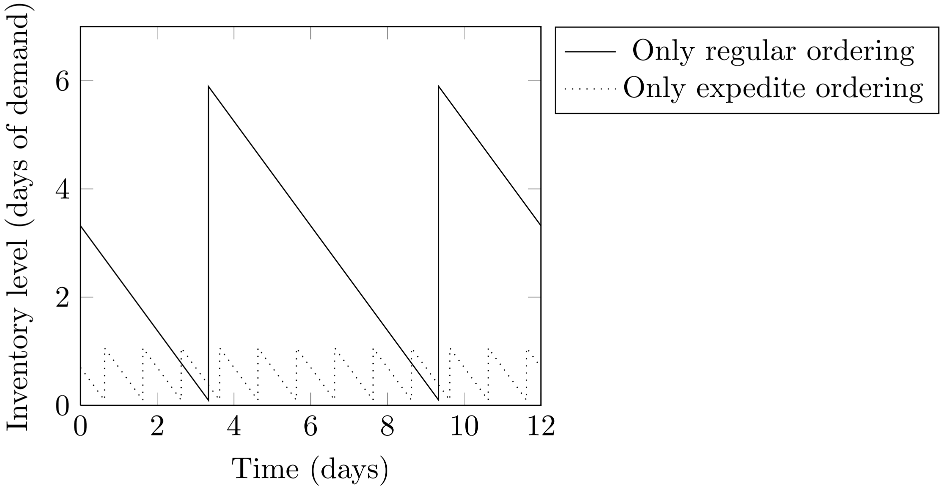

Figure 5.2: Sawtooth figure of inventory levels.

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These 50,000 demand observations are sufficient to ensure near-optimal policy outcomes. The resulting DIP in Table 5.4 reveal that including more cost for shelf life losses will lead to policies that are more sensitive to expected shelf life losses. The - indicates that products will never be ordered using that specific transportation mode, whereas the 0 in Table 5.4 indicates that products will only be ordered using that transport mode if there is a negative expedited inventory position. The latter may occur if current shortages are higher than the products that will be delivered within the expedited order lead time. The effect of ordering only once a week using regular transport or daily using expedited transport on the inventory level can be observed in Figure 5.2.

Order up to position	Expedite mode (days of demand)	Regular mode (days of demand)
DIP without decay costs	0	7.017
DIP + 0.25 * decay costs	1.036	4.034
DIP + 0.50 * decay costs	1.039	3.028
DIP + 0.75 * decay costs	1.039	2.018
DIP + 1.00 * decay costs	1.041	-

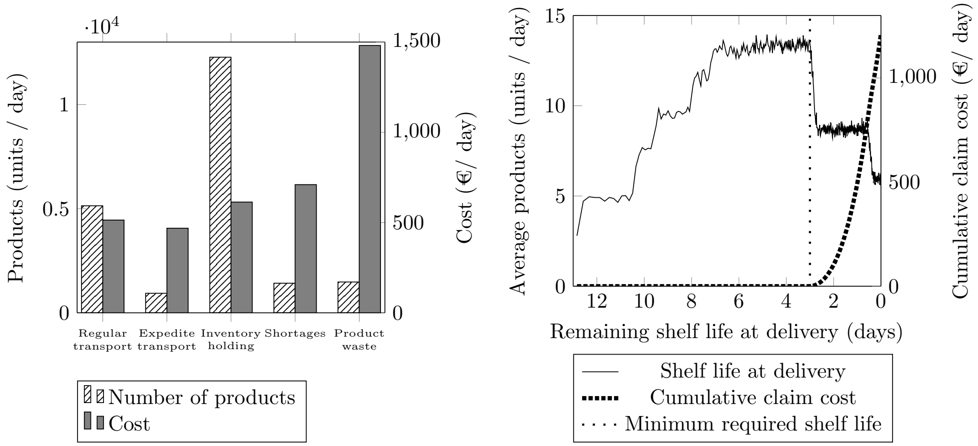
Table 5.4: Dual-index order-up-to positions.

5.4.4 Simulated system

To assess the effectiveness of the DIP presented in Table 5.4 with respect to performance indicators presented in section 5.4.2, we developed a hybrid discrete-continuous simulation tool. This model includes 10 retail outlets to simulate a realistic chain. Customer purchases at these retail outlets follow a Poisson distribution with a rate of $\lambda = 600$ units/day at each of the retail outlets; this corresponds to 0.150 tons of expected demand per shop, which is the average quantity supplied by the distributor in this case study. The expected demand is assumed to be constant throughout the week. We assumed that the customer demand rate parameter λ of the Poisson distribution is correctly estimated at each of the retail outlets, and that this information is used for inventory control purposes. Inventory control at the retail outlet is performed by employing a base stock policy targeting a service level of $\alpha = 0.95$. Use of base-stock policies is common in retail environments, where the service level most typically used is 95 % [Smith and Agrawal, 2000]. If there are shortages at a retailer, consumer demand is backordered until the next replenishment arrives, so as to comply with the backordering assumptions of the DIP. Due to the high target service level, differences between a situation with and without backordering are limited [Bookbinder and Tan, 1988]. The exact time of each retail order is randomized (i.e. noon ± 5 minutes, uniformly distributed) to simulate small discrepancies in the automatic ordering system clock and prevent systematic differences between product quality and quantity delivered to the different retail outlets.

We distinguished two consumer groups. Following Rijgersberg et al. [2010], 40 % of consumers specifically select the freshest product at the retail shelf (last in, first out), whereas the remaining 60 % simply select the product that appears at the front of the retail shelf (first in, first out). This 40/60 distribution is close to the 42 and 58 % observed by Tsiros and Heilman [2005]. The initial quality of strawberry punnets is randomly distributed with an average of 0.798 % and a standard deviation of 0.709 %, based on Hertog et al. [1999]. Strawberry quality deteriorates continuously depending on the environmental conditions. The quality integration step is fixed to one hour, since smaller integration steps did not prove to be beneficial. We assumed that once a strawberry punnet enters a given environment, the strawberry is immediately at the environmental temperature.

The chain simulation is implemented using the Stochastic Simulation in



(a) Complete set of solutions.

(b) Subset of solutions.

Figure 5.3: Performance of the standard scenario with respect to (a) transport, inventory, shortages and waste (b) retailer claim cost and shelf life of delivered products.

Java (SSJ) library. For scenario assessment we used a simulation length of 264 days, which proved to be sufficient to obtain stable simulation outcomes. We excluded performance data gathered during the first 14 simulated days from the analysis to ensure a representative filling of the complete supply chain. To ensure comparable results for the different scenarios, random numbers were initialized with the same seed.

5.4.5 Scenario comparison

The performance of the standard scenario (i.e. DIP obtained with normal cost parameters) with respect to the defined KPIs can be seen in Figure 5.3. The results clearly show that applying DIP with standard cost parameters would result in poor product quality and large amounts of waste. A significant number of products are ordered using expedited transport, despite an expedited order-up-to position of 0. This is caused by products that spoil at the distributor, which results in shortages at the distributor.

The aggregated performance data of all five scenarios can be found in Figure 5.4. The figure shows that including costs for shelf life losses in the DIP has the following six consequences: (1) a reduction in regular transport costs, indicating that fewer strawberries are shipped using the regular transport mode; (2) an increase in expedited transport costs, indicating

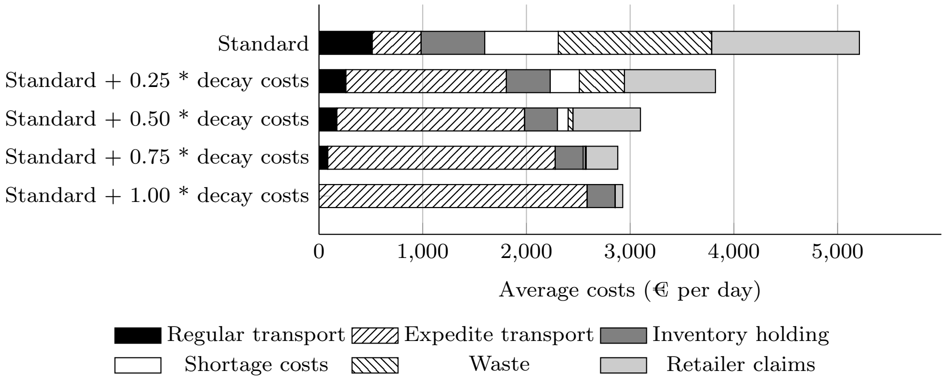


Figure 5.4: Performance analysis of dual-index policy.

that more strawberries are shipped using the expedited transport mode; (3) a reduction of inventory costs, indicating that the average stock levels are lower; (4) a reduction of shortage costs, indicating that the distributor is able to deliver more reliably; (5) a reduction in distributor waste, indicating that fewer strawberries spoil at the distributor; and (6) a reduction of retailer claim costs, indicating that the strawberries delivered to the retailer have a higher remaining shelf life.

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Figure 5.4 reveals that the sum of cost drivers traditionally used in the adopted order policy (i.e. regular transport costs, expedited transport costs, inventory holding costs, and shortage costs) increases if costs for shelf life losses are included while determining the DIP. However, this cost increase is cancelled out by reductions in product waste and retailer claim costs, which reduces the overall cost.

5.4.6 Generalizability of findings

To assess whether the results presented in section 5.4.5 are generalizable, we generated two alternative sets of scenarios. The first set of scenarios considers a higher initial product quality by reducing both the initial infection level and variation in infection level by 50 % (i.e. $N_0 = 0.399 \pm 0.3545$ %). In the second set of scenarios, the quality decay rate during transport and storage steps is reduced by applying modified atmosphere storage with O_2 and CO_2 concentrations of 2.5 and 15 %, respectively (following Zhang et al. [2006]). This reduces the microbiological growth rate by approximately 40 %. The resulting DIPs are presented in Table 5.5 and

Table 5.5: Dual index policies used for robustness analysis.

	Order-up-to positions (days of demand)			
	Higher initial quality		Modified atmosphere storage	
Decay included	Expedite	Regular	Expedite	Regular
no decay	0	7.017		7.017
0.25 * decay	1.035	4.099	1.035	4.103
0.50 * decay	1.040	3.070	1.039	4.005
0.75 * decay	1.039	2.064	1.039	3.006
1.00 * decay	1.039	2.029	1.039	2.033

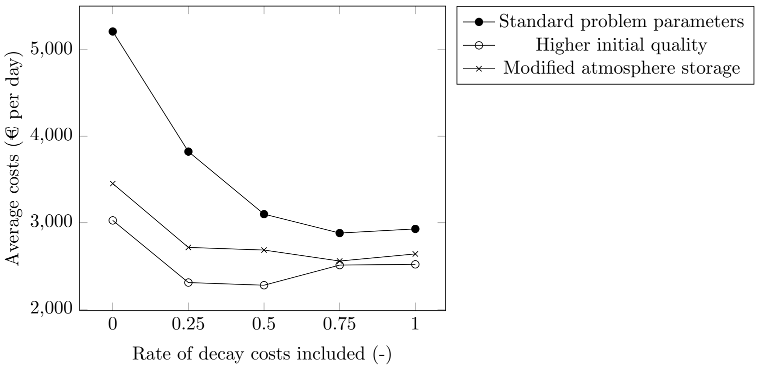

Figure 5.5: Performance analysis of DIPs obtained with alternative parameter settings.

their performance is assessed using the chain simulation tool.

The aggregate performance data presented in Figure 5.5 shows the effect of changes in initial quality, and modified atmosphere storage on overall costs. The results the figure also show that DIP derived with cost parameters that include costs for expected shelf life losses react effectively to changes in initial product quality, or quality decay rate. The combined results presented in Figure 5.5 show that the developed method is effective at identifying a trade-off between various cost drivers in perishable product supply chains.

The results presented in Figure 5.5 only include performance indicators related to logistics, waste and quality decay. The question of whether the benefits of obtaining products with a higher initial quality or use of modified atmosphere outweigh the cost of achieving higher product quality or implementing modified atmosphere storage should be investigated separately.

5.5 Conclusions and discussion

The results of the presented case study confirm the hypothesis that existing sourcing strategies are ineffective at providing an appropriate performance in international perishable product supply chains, and would actually result in large amounts of product waste and poor delivered product quality. Of course the exact impact depends upon the specific case characteristics. The case results also confirm the hypothesis that performance improvements can be achieved in perishable product supply chains by including costs for expected shelf life losses in logistics decision making. As a result, product waste and retailer claim costs were significantly reduced, which outweighed increases in transportation costs. Analysis of a number of key parameters (i.e. the initial product quality, and the rate of quality decay) confirmed the robustness of the presented approach.

The presented methodology shows that decision makers in perishable product supply chains should achieve a trade-off between logistics cost drivers and performance indicators related to product quality. Furthermore, by presenting a method to analyse trade-offs between shelf life losses and logistics cost we provide a method to reduce food waste. The study therefore contributes to worldwide efforts to reduce food waste by presenting a generically applicable methodology to improve the effectiveness of sourcing strategies, thereby addressing one of the research gaps identified by Rajurkar and Jain [2011].

Effective use of product quality information is also expected to aid decision makers with the delivery of products of the right quality at the right place and time. This may lead to more frequent re-stocking and lower inventory levels, thereby changing the design of perishable supply chains; this is a research area that is still in its infancy [Akkerman et al., 2010, van der Vorst et al., 2011].

The presented methodology is expected to reduce food waste and, consequently, reduce environmental load. However, whether this reduction in environmental load will compensate for the increase in emissions related to expedited (air) transport is an interesting subject for further research. In this case study a linear value decrease of products with reduced shelf life is considered, both while determining DIP and while discounting products delivered to retailers with insufficient shelf life. In future research it would be interesting to assess what effect alternative price discount strategies would have on the effectiveness of the proposed strategy. It might also be interesting to investigate whether including costs for expected shelf life reductions while obtaining policies yields similar results if applied in supply chains with other perishable products or policies.

Acknowledgements

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Chapter 6

Use of form postponement in the reduction of food waste under product quality decay.

In this chapter we study research question 4:

> *Can form postponement be used to limit food waste and quality decay in food supply chains?*

This chapter is based on an article submitted to a scientific journal:

Rijpkema, W.A., Rossi, R., Lopez-Galvez, F., and van der Vorst, J.G.A.J.

Abstract

Recent research has indicated that approximately one third of all food produced for human consumption worldwide is lost or wasted. To reduce food waste, an effective supply chain design is required that allows decision makers to react to demand changes while limiting food quality degradation.

This case study assesses whether a supply chain design strategy called form postponement may be used to reduce waste in an international lettuce supply chain. Various supply chain scenarios are defined that differ in the location and timing of lettuce processing and bagging. The performance of these scenarios is assessed using a chain simulation tool, which models the flow of both unprocessed (whole crop lettuce) and processed (processed and mixed lettuce) produce and predicts quality decay of both lettuce types using spoilage models.

Simulation results reveal that form postponement may significantly improve product quality at the point of sale and reduce product waste. Waste reductions of up to 1.28 % and reductions of product age at the point of sale of 8.75 % were observed. Storing both generic and processed lettuce at retail outlets was shown to bring benefits, although for either very low or high demand volumes, keeping an extra type of inventory may not be beneficial. The sensitivity of the simulated system was assessed with respect to changes in required service level, product volume, and quality decay properties.

This case study contributes to worldwide efforts to reduce food waste by showing how form postponement may be used to deal with the specific characteristics of food supply chains. In addition, by combining quality decay models in a chain simulation model we provide an example of how quantitative models may be used to support the design of food supply chains.

Keywords food supply chains, food waste, form postponement, customer order decoupling point, supply chain design

6.1 Introduction

During past decades, food supply chains have become globalized because consumers are demanding year-round availability of fresh products in retail outlets. Producers must source seasonal products from multiple climate regions throughout the year. A specifically designed supply chain is required to supply consumers with fresh products of high quality while minimizing overall costs and product waste [Ahumada and Villalobos, 2009, van der Vorst et al., 2009]. An ineffectively designed perishable product supply chain may lead to poor product quality, and ultimately, food waste. Food waste occurs when food appropriate for human consumption is discarded, whether it is kept beyond its expiration date or left to spoil [FAO, 2013b]. A review of published articles indexed by Sciencedirect showed that the number of articles using the search term ”food waste” increased from 44 in 2000 to 965 in 2013. Despite this increased attention to perishable product supply chains and food waste reduction, recent research indicates that food waste remains unacceptably high; approximately one third of all food produced for human consumption in the world is lost or wasted [FAO, 2013a]. To a large extent, quality decay of perishable products drives this loss. Food waste can result in hunger, poverty, reduced income generation, and reduced economic growth. It also is a waste of production resources such as land, water, energy, and other inputs, and thereby negatively affects the sustainability of food production systems [Kaipia et al., 2013, Aggidis et al., 2013]. The design and management of perishable product supply chains is a key determinant of food waste, and specific strategies for food waste reduction need to be developed [Rajurkar and Jain, 2011].

Despite the importance of specific strategies for food waste reduction, few studies have taken the dynamic decay of perishable product quality into account in the design of perishable product supply chains [Bakker et al., 2012]. In this thesis, we examined whether an important supply chain concept called *form postponement* can be used in perishable product supply chains to improve product quality and reduce food waste. Form postponement is a supply chain concept in which processing actions that make a generic product specific to a customer or end product are delayed to allow supply chain actors to respond more efficiently to changes in demand and to reduce inventory levels [Boone et al., 2007]. Lowering the inventory level may benefit food supply chains that face product waste. Thus, the research question that follows is: Can form postponement be used to limit food waste and quality decay in food supply chains? We investigated this question through a case study of an international iceberg lettuce supply chain, considering different supply chain scenarios both with and without postponement. Using a chain simulation tool, we assessed the performance of these scenarios with respect to product waste, obtained service level, and (logistic) cost.

This chapter is structured as follows: Section 6.2 provides an overview of the relevant literature areas and section 6.3 gives an overview of the applied research methodology. The case study presented in this chapter is described in section 6.4, whereas details on modeling and simulation are presented in section 6.5. The results of the simulation study are presented in section 6.6, while section 6.7 offers some conclusions, discussion, and recommendations for future research.

6.2 Position in literature

In this section, we present the findings of several recent literature reviews in areas relevant to this case study. First, we provide an overview into causes for food waste (section 6.2.1), followed by an overview of literature contributions in the field of perishable supply chain design (section 6.2.2). The concept of form postponement is discussed in section 6.2.3.

6.2.1 Causes for food waste

In recent years, there has been increasing attention on food waste reduction, both in society and in research. Several reports estimated that approximately one third of the food produced for human consumption is either lost or wasted [FAO, 2013a, Aggidis et al., 2013]. In Europe, these losses are responsible for an average emission of nearly 700 kilograms of CO_2 equivalents per year per citizen [FAO, 2013a].

Food waste arises in all types of products, with the highest losses in Europe occurring in roots and tubers (52 %), fruits and vegetables (47 %), and cereals (34 %) [Gustavsson et al., 2011]. Furthermore, waste occurs at all stages of the food supply chain (production, post-harvest handling and storage, processing, distribution, and consumption) for a variety of reasons; whereas in low-income regions, food losses occur mainly in the early stages of the supply chain; in high income regions, losses occur more in the downstream phases of the supply chain [FAO, 2013a]. In medium- and high-income countries, food waste is caused to a large extent by spoilage or limited remaining shelf life [Gustavsson et al., 2011]. Research in the UK identified several causes for food waste in the supplier-retailer interface, including (i) a combination of poor forecast accuracy and short shelf-life, (ii) retailers that balance on-shelf availability and waste, and (iii) frequent overstocking by suppliers to prevent penalties [Mena et al., 2011]. In the last two decades, an increase in these losses has been spurred by a culture of abundance and the perception and expectation that displaying large quantities and having a wide range of products and brands leads to increased sales [FAO, 2013b]. To deal with the specific characteristics and requirements of food supply chains and to minimize food waste, an effective supply chain design and management is required [Rajurkar and Jain, 2011].

6.2.2 Perishable Product Supply Chain design

In both the academic and business worlds, supply chain management and design have received a great deal of attention. There is a general understanding that the design of a supply chain should be based on the combination of the strategic objectives of the involved organizations and specific characteristics of its supply chain [Simchi-Levi et al., 2007, Slack et al., 2010]. Recent literature reviews [Akkerman et al., 2010, Karaesmen et al., 2011, Rajurkar and Jain, 2011] have shown that the characteristics of perishable product supply chains, such as deteriorating product quality and heterogeneous product supply, complicate the design and management of these supply chains. Their design should aim to satisfy logistics goals (such as cost and delivery service requirements) and ensure timely delivery of products of the right quality at the right place and time [van der Vorst et al., 2011]. In addition, agricultural produce must reach consumers efficiently to minimize food waste [FAO, 2013b].

An effective supply chain design and management must include specific strategies for food waste reduction [Rajurkar and Jain, 2011]; however, few studies have taken the dynamic decay properties that cause spoilage into account [Bakker et al., 2012]. A number of strategies have been proposed to support the effective design and management of food supply chains. For example, van der Vorst et al. [2011] proposed an integrated approach towards logistics, sustainability, and food quality analysis that is supported using a simulation environment. This supply chain redesign approach may be used to analyze and support innovative business strategies that are aimed not solely at improving logistics performance, but also at food quality preservation and food waste reduction. A number of supply chain strategies have been proposed to preserve food quality and reduce food waste, such as incorporating costs for expected quality decay while sourcing perishable products [Rijpkema et al., 2014]. In this case study, we investigated the supply chain strategy called postponement, which is a common business strategy for reduction of supply chain inventory levels [van Hoek, 2001]. As a result, actors in food supply chains may be able to implement this strategy because lower inventory of perishable products and shorter throughput times may reduce food waste.

6.2.3 Form postponement in food supply chains

Postponement refers to a concept in which supply chain activities are delayed until a demand is realized [van Hoek, 2001]. Research suggests that postponement can be used to deal with large demand variety and improve responsiveness while reducing transportation expenditures, inventory level, and product obsolescence [Lee and Billington, 1994, van Hoek, 2001]. Market, product, and production characteristics influence the choice of a postponement strategy [Olhager, 2003]. Market characteristics relate to lead-time, demand volatility, volume, product range, and order size and frequency, whereas product characteristics include the modular design of products and the opportunities for customization.

Van Hoek [2001] distinguished the different types of postponement, of which form postponement (FP) is usually seen as the most common type. FP implies delaying those steps that make a generic product specific to a customer or end market. The point in the manufacturing value chain where the product is linked to a specific customer order is also called the customer order decoupling point [Olhager, 2010]. Although there has been quite some research into postponement practices (see literature reviews by van Hoek [2001] and Boone et al. [2007]), the number of studies concerning the use of FP in food supply chains is limited [van Kampen and van Donk, 2013].

Morehouse and Bowersox [1995] predicted that half of all inventory throughout food supply chains would be retained in a semi-finished state by 2010. Other authors [van Hoek, 1999, Yang and Burns, 2003] found implementation of FP in food supply chains is often hindered by specific processing characteristics. The limited number of applications of FP in food processing can be found mainly in postponed packaging and labeling (e.g. Cholette [2009], Wong et al. [2011], van der Vorst et al. [2001]). It is therefore not clear what effect typical food processing industry characteristics have on applicability of FP [van Kampen and van Donk, 2013]. For example, food products have the characteristic of perishability, and FP is a commonly accepted means to reduce inventory; however, FPs effect on food quality and product waste has not been studied, to our knowledge. We hypothesize that application of FP to perishable product supply chains can improve the product quality of sold products, and reduce the quantity of products lost through obsolescence. We tested this hypothesis using a case study in which FP was considered in an international iceberg lettuce supply chain.

6.3 Research methodology

To address this research goal, we employed case study research, using a combination of methods. Section 6.3.1 provides a short introduction to the required supply chain analysis and definitions of key performance indicators. A description of scenario development is provided in section 6.3.2, followed by an outline of the applied chain simulation modeling techniques are outlined in section 6.3.3.

6.3.1 Supply chain analysis

As noted, the choice of a postponement strategy depends on the specific supply chain characteristics. Therefore, we first conducted a supply chain analysis of the case under consideration to obtain an overview of these characteristics and gather the data required for quantitative analysis. All supply chain processes were described and analyzed in detail to get a full understanding of their mechanisms and of the dynamics and objectives of the system. For an overview of supply chain analysis methods in perishable product supply chains, see van der Vorst and Beulens [2002]. We also defined key performance indicators (KPIs) that reflect the performance of the respective processes and supply chain. These KPIs may include performance indicators commonly found in literature (such as transportation cost, storage cost, shortage cost) and performance indicators specific to perishable products (such as product waste and quality discounts) [Aramyan et al., 2007].

6.3.2 Scenario development

A number of supply chain scenarios were defined to reflect both the current supply chain structure and scenarios for future operation. These scenarios were defined based on a literature review, expert interviews, the available infrastructure, and an analysis of gathered data. The consulted experts included researchers in the field of keeping quality of vegetable products, as well as logistics experts from both lettuce processing and distributing companies.

6.3.3 Simulation modeling

Effective design of perishable product supply chains requires modeling efforts, with the aim to satisfy both logistics goals (e.g. cost and delivery service requirements) and to ensure timely delivery of products with the right quality at the right place and time [van der Vorst et al., 2011]. Several model types can be applied to support perishable product supply chain design that often use either simulation or optimization. For example, Rijpkema et al. [2014] introduced a simulation environment to assess perishable product supply chain configurations, and Zhang et al. [2003], used optimization to minimize supply chain storage and transportation costs while penalizing and constraining product quality decay.

We used a discrete event simulation model to assess the effectiveness of the supply chain scenarios with respect to the defined performance indicators. Discrete event simulation is often used to study supply chain configurations, as their complexity obstructs analytic evaluation [van der Zee and van der Vorst, 2005]. This complexity of supply chains usually stems from the presence of multiple (semi-)autonomous organizations, functions, and stakeholders within a dynamic environment [van der Zee and van der Vorst, 2005]. In this case, a discrete-continuous simulation tool was employed, which included both discrete features (i.e. individual products moving through a supply chain) and continuous factors (i.e. deteriorating product quality). This tool allowed for in-depth analysis of supply chain performance. For an elaborate overview of discrete-continuous simulation models, see Zeigler et al. [2000].

Table 6.1: Supply chain conditions for Spanish lettuce shipped to Belgium.

	Duration (hours)	Temperature (°C)	σ (°C)
Harvesting and storage in Spain	$26 \leq \leq 32.5$	8	2
Transport producer - distributor	36	3	0.25
Storage at distributor	variable	3	0.25
Transport distributor - retailer	± 1	5	0.25
Storage at retailer	variable	5	1

6.4 Case study

This section presents a case study of an international iceberg lettuce supply chain under study in the EU project *Veg-i-Trade*, in which different supply chain scenarios were considered. The structure of this chain is derived from data collected during several company interviews with a producer in Spain and an international distributor of fresh vegetables. The company also provided data on a prototype supply chain network for the Spanish iceberg lettuce trade.

The application of form postponement is presented in the following way: section 6.4.1 describes the supply chain, and section 6.4.2 outlines the appropriate supply chain performance indicators. Section 6.4.3 describes the supply chain scenarios.

6

6.4.1 Supply chain description

The case involves a Belgian distributor of fresh vegetables. For confidentiality reasons, the generic terms supplier, distributor, and retailer are used instead of the actual company names. For this case, the supply chain network included an iceberg lettuce producer in Spain, a distributor in Belgium, and retail outlets in Belgium. We limited the analysis to lettuce originating from Spain, sold as fresh-cut in retail outlets. The temperature data used was for the region in February, when the distributor sources his lettuce exclusively from Spain. Following is a description of the individual supply chain parts and the most important processing steps. Data on environmental conditions throughout the supply chain, obtained from industrial partners, is summarized in Table 6.1.

Producer

The Spanish producer harvests iceberg lettuce each day between 05:30 and 12:00. Directly after harvest, the lettuce crops are bagged in a plastic film, packed into 24-piece cartons, and temporarily stored. The storage temperature is comparable to the outside temperature because rapid chilling directly after harvest may lead to harmful condensation on the lettuce crop. As a result, there is no distinction between temperature differences in the field and the temporary storage. The harvested and packed crop is transported in the afternoon to a local distributor, where it is either processed to fresh-cut lettuce or shipped to customers as whole crop lettuce. The harvested lettuce is either shipped to the Belgian distributor in the early afternoon (± 14.00) the following day or is sold to other customers.

Distributor
The distributor places orders between 22:00 and 24:00 hours each day for either whole crop lettuce or cut lettuce. The producer ships the distributor orders with day-fresh produce in the early afternoon of the following day. The shipped orders arrive at the distributor between 00:00 and 05:00, after a transportation period of approximately 36 hours. After arrival, the distributor stores the produce and ships his orders to customers based on a first-in, first-out policy.

Retail outlets
Retail outlets open each day between 08:00 and 20:00. After closing, retailers send their replenishment orders to the distributor between 20:00 and 22:00. The distributor ships these orders in the early morning for arrival at the retailer between 06:00 and 08:00, before the retail outlets open. Products are regularly rearranged on the shelves, with the oldest product in front, although some consumers specifically look for the freshest products.

Processing and packaging
Processing whole crop iceberg lettuce into fresh-cut lettuce can be done at different positions in the supply chain. A schematic overview of the lettuce supply chain with different processing positions is shown in Figure 6.1. During processing, lettuce heads are removed and leaves are cut, after which the cut leaves are washed in cold water. The lettuce is dried in a centrifuge, mixed with other types of lettuce or greens, if required, and packed in bags made from a special plastic film. The film maintains a low oxygen concentration inside the bags in order to avoid browning and reduce respiration of the lettuce tissue. Bags are placed in cartons and either stored or immediately shipped to a customer.

Postponed processing
As whole crop lettuce is processed into end products of various sizes and composition, the position where the whole lettuce crop is processed has im-

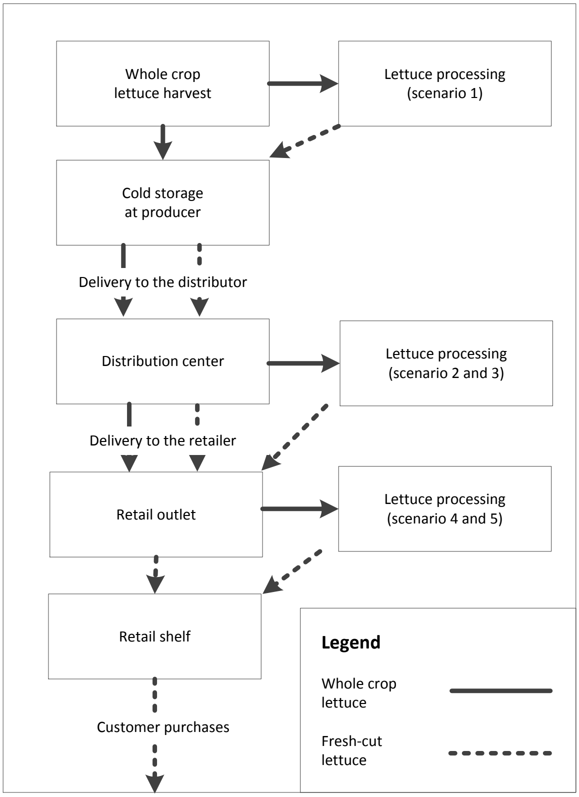


Figure 6.1: Schematic overview of lettuce supply chain (adapted from Gorny et al. [2006]).

plications for the order aggregation. If the inventory is whole crop lettuce, demand can be aggregated for all end products, but if the inventory is processed end products, then each product type must be ordered individually. As a result, the total safety stock required to achieve a certain service level will be higher if individual end products are kept in inventory compared with a situation in which end product demand can be fulfilled from a generic inventory of whole crop lettuce. Therefore, orders upstream of lettuce processing are based on the aggregated demand for all lettuce-based products, because this demand can be fulfilled using a generic inventory of whole crop lettuce. Orders downstream of processing are end product specific.

6.4.2 Key performance indicators

The KPIs used in this case study were selected in collaboration with the industrial partner based on performance indicators commonly used in inventory management literature (e.g. Silver et al. [1998]) and that reflect the scope of this research (i.e. the interaction between FP and food waste). The adopted KPIs do not reflect cost drivers because a cost-benefit analysis is beyond the scope of this exploratory research. The KPIs are food waste, product quality, and customer service level. Product waste is the quantity of whole crop lettuce and fresh-cut lettuce that is discarded because it no longer meets the required quality specifications at retail outlets. An elaborate description of the adopted quality measures is shown in the Section 6.5.1; the service level is measured as the proportion of consumers in retail outlets whose needs are satisfied with a product of sufficient quality.

6.4.3 Scenario description

The Belgian distributor currently buys all fresh-cut lettuce in a processed form, but would consider buying and processing whole crop lettuce at the distributor plant in Belgium. However, the distributor is unsure how processing at a later point in the supply chain will affect his overall performance. In particular he would like to know how this change may affect (i) the quantity of produce lost through obsolescence, (ii) the quality of sold produce, and (iii) the probability of stockouts in retail outlets. To answer these questions, five scenarios (a base scenario (scenario 1) and four alternatives) were defined and assessed using a chain simulation tool. In the first or base scenario, the Spanish producer processes all lettuce. In the second scenario, whole crop lettuce is processed directly after arrival at the distributor in Belgium and stored until customer orders arrive. In the third scenario, whole crop lettuce is ordered and stored at the distributor and the lettuce is processed after arrival of retailer orders. In the fourth scenario the retailer orders only whole crop lettuce, and cuts and processes the product and refills the shelves twice a day, directly before opening (08:00) and at 14:00. Therefore, the retailer holds an inventory of both whole crop and fresh-cut lettuce. In the fifth scenario, the retailer orders and stocks only whole crop lettuce, but meets customer demand for fresh-cut lettuce by processing it upon request at the moment it is sold. This final scenario

Table 6.2: Scenario details.

Scenario number	Processing position	Triggered by
1	Producer	Order arrival
2	Distributor	Product arrival
3	Distributor	Order arrival
4	Retailer	Product arrival
5	Retailer	Order arrival

aligns with developments observed in retail outlets, where products are finalised on demand at retail outlets. A schematic overview of the storage and processing points in the different scenarios is shown in Figure 6.2. Note that in this figure the storage points before processing represent storage of whole crop lettuce, whereas inventory points after processing represent storage of processed lettuce. Table 6.2 shows the position of lettuce processing and the action that triggers processing.

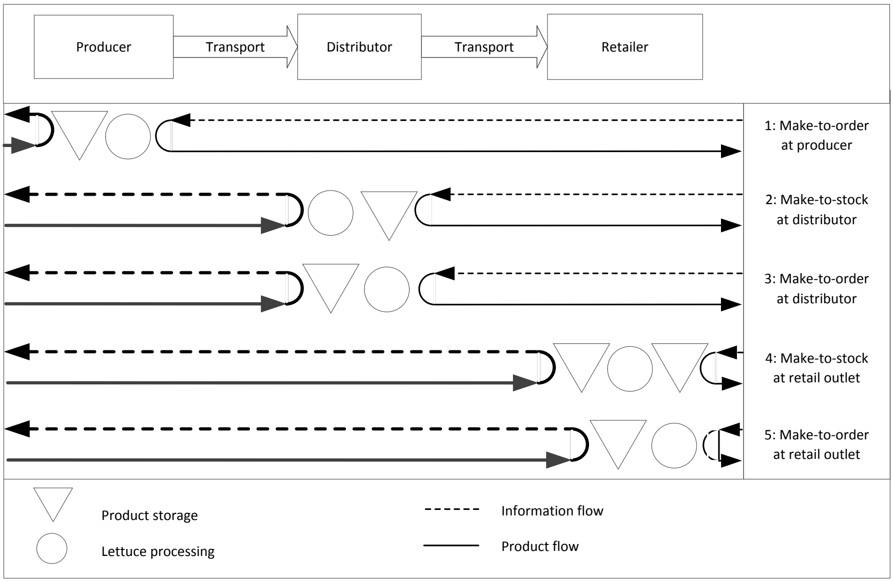


Figure 6.2: Schematic scenario overview.

Table 6.3: Quality model parameters (source: Lopez-Galvez [to appear]).

Symbol	Value	Unit	Description
V_1	$4.80 * 10^{-13}$	[ml O_2]*kg^{-1}*day^{-1}	Respiratory parameter 1
V_2	0.107	°K^{-1}	Respiratory parameter 2
K_m	$7.526 * 10^{-2}$	[ml air]*[ml O_2]$^{-1}$	Michaelis-Menten constant
c	0.137	$[Q^b] * day^{-1}$	Quality decay rate at T_b
T_b	283.624	°K	Reference temperature for quality decay
α	-13.264	-	Oxygen sensitivity quality decay
R	8.314	J*mol^{-1}*°K^{-1}	Ideal gas constant
O_2^o	0.209	[ml O_2]*[ml air]$^{-1}$	Ambient oxygen concentration

6.5 Modeling and simulation

This section describes the chain simulation tool used to simulate the supply chain scenarios presented in the previous section. The quality measures included in this simulation tool are presented in section 6.5.1; the supply chain details used in the simulation tool are described in section 6.5.2, and the implementation details are presented in section 6.5.3.

6

6.5.1 Quality modeling of lettuce

The quality of iceberg lettuce can be expressed using a number of quality parameters, such as weight loss, crop browning, nutritional value, and other physicochemical characteristics [Moreira et al., 2006]. We adopted visual quality as the key determinant of lettuce quality, which is commonly measured using a hedonic scale introduced by Kader et al. [1973]. In this scale, quality levels between 1 and 9 are used to denote a visual quality from extremely poor (1) to excellent (9). Models that predict quality evolution are available for both whole crop and fresh-cut iceberg lettuce. The parameters and variables used are shown in Table 6.3.

Quality of whole crop lettuce

Visual quality of whole crop lettuce was predicted using a quality predictive model in combination with temperature data. This quality model was obtained by fitting visual quality data of whole crop lettuce stored at temperatures of 0, 5, and 10 °C from Pratt et al. [1954]. The resulting quality evolution model, which yielded an R^2 of 0.944, is given in the equation 6.1.

$$\frac{dQ^w}{dt} = 3.736 - 0.0143T \tag{6.1}$$

Quality of fresh-cut lettuce

Fresh-cut lettuce is typically packed in a plastic film that is semipermeable

Table 6.4: Quality model variables (source: lettuce producer).

Symbol	Unit	Description
Q^w	hedonic scale, 1 to 9	Quality level whole crop lettuce
t	day^{-1}	Time
T	°K	Temperature
O_2^i	[ml O_2]*[ml air]$^{-1}$	Oxygen concentration in lettuce bag
Q^b	hedonic scale, 1 to 9	Quality level lettuce bag

Table 6.5: Lettuce bag characteristics.

Symbol	Value	Unit	Description
W	0.25	kg	Lettuce weight inside bag
P_{ref}	16485	[ml O_2]*μm*m^{-2}*day^{-1}*atm^{-1}	Reference permeability of plastic film
E_p	45300	J*mol^{-1}	Permeability activation energy
T_p	280.15	°K	Reference temperature for P_{ref}
A	0.12	m^2	Bag surface
L	35	μ m	Diameter of the plastic film
V	1200	[ml air]	Air volume inside bag

for oxygen. As the permeability of this plastic film to various gases determines the atmospheric conditions in the headspace, the properties of the plastic film will ultimately affect the shelf life of the product [Mattos et al., 2012]. To predict the atmospheric conditions in the headspace, an oxygen mass balance was employed to approximate the oxygen content inside the lettuce bag based on oxygen inflow (i.e. the oxygen that enters the bag through the permeable film) and the oxygen consumption (i.e. the oxygen consumed by the crop inside the bag). The change in oxygen concentration within the lettuce bag was approximated using the equation 6.2, taken from van Bree et al. [2010]. The variables used in this equation are defined in Table 6.4. Parameter data on the lettuce bag, provided by the lettuce processor, are presented in Table 6.5.

$$\frac{dO_2^i}{dt}V = \overbrace{\frac{P_{ref}A\exp[\frac{E_p}{R}(\frac{1}{T_p}-\frac{1}{T})](O_2^o-O_2^i)}{L}}^{\text{Oxygen inflow}} - \overbrace{\frac{V_1WO_2^i\exp[V_2T]}{K_m+O_2^i}}^{\text{Oxygen consumption}} \tag{6.2}$$

Visual quality evolution of fresh-cut bagged lettuce is predicted using the equation 6.3, taken from Lopez-Galvez [to appear].

$$\frac{dQ^b}{dt} = \log[1+\exp[c(T-T_b)]\exp[\alpha(0.0255-O_2^i)]] \tag{6.3}$$

The initial quality of the whole crop lettuce was considered to be uniformly distributed between 8.5 and 9 on the hedonic scale, which Kader et al. [1973]

classified as near excellent. This is done so as to simulate the natural variability in initial product quality. The range between 8.5 and 9 was selected as the quality levels of freshly harvested lettuce typically reported in the literature (e.g. Lopez-Galvez [to appear], Pratt et al. [1954]) are within this range. Following López-Gálvez et al. [1996], who found that iceberg lettuce heads can be stored for up to 14 days without a decrease in shelf-life of the salad product as compared to product prepared from non-stored lettuce, the visual quality was considered unaffected by processing (i.e. quality of whole crop lettuce before processing was equal to the quality level of fresh-cut lettuce after processing). The oxygen concentration inside the lettuce bag directly after processing was considered to be 5 %. Lettuce is considered unacceptable if the visual quality is below 6.0, according to López-Gálvez et al. [1996]. Figure 6.3 shows the effect temperature has on product quality decay of whole crop and fresh-cut lettuce with the provided parameters and variables.

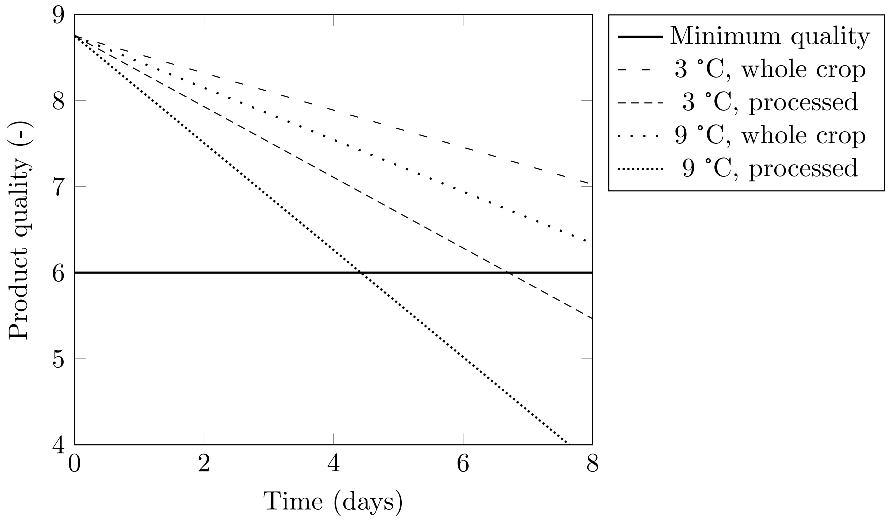


Figure 6.3: Quality evolution of whole crop and fresh-cut bagged lettuce.

6.5.2 Modeled system

Consumers

Consumers in this case were those purchasing a single end product: bagged fresh-cut lettuce. Customer purchases at retail outlets followed a Poisson distribution with a rate of 12 units per day at each of the retail outlets and were assumed to be constant throughout the week. Following Rijgersberg et al. [2010], we randomly assigned consumers to one of two groups: 40% of the consumers specifically select the freshest product on the retail shelf (last in, first out), and the remaining 60% simply select the product that appeared at the front of the retail shelf (first in, first out).

Retailer

Ten retail outlets were included in the model to simulate the current situation. We assumed that the estimated customer demand rate at each of the retail outlets was used for inventory control by employing a base stock policy targeting a service level of 95%. Base stock policies are commonly used in retail environments, and the most typical service level most typically is 95 % [Smith and Agrawal, 2000]. As in scenario 4, both an inventory of whole crop and fresh-cut lettuce was kept at the retailer, and the adopted service level for the individual inventories was set at $\sqrt{0.95}$. This ensured that an overall service level of at least 0.95 was obtained. Shortages at a retailer were treated as lost sale. The exact timing of each retail order was randomized (i.e. 21:00 $\pm$ 60 minutes, uniformly distributed) to simulate small discrepancies in the automatic ordering system clock and to prevent systematic differences between product quality and quantity delivered to the different retail outlets.

6

Distributor

Inventory control at the distributor was based on a base stock policy targeting a service level of 95%. If there were shortages at a distributor, this demand was back-ordered and the ordered products were delivered to the retailers at the earliest opportunity.

Position of processing

We considered the aggregated demand for seven end products derived from whole crop lettuce, all of which had similar demand and physical characteristics. If the supply of whole crop lettuce was insufficient to fulfill demand for all end products, the order fill rate was proportional to the rate of total demand that could be fulfilled.

6.5.3 Implementation details

The described system was implemented using the Stochastic Simulation in Java (SSJ) library (http://www.iro.umontreal.ca/~simardr/ssj/indexe.html). SSJ is an object-oriented simulation library that provides facilities for combined discrete-continuous simulation. For each continuous object in the system, the associated differential equation and initial condition is provided, and integration of dynamic properties is automatically performed. In this case, the included simulation unit corresponded to a single lettuce bag, and whole crop inventory-keeping units were registered in number of lettuce bags. The storage and transportation temperatures of whole crop or fresh-cut lettuce were randomly drawn following the given average temperature and the distribution around this average. The storage and transportation temperatures were considered as constant during a storage or transportation period. To ensure comparable results for the scenario analyses, common random numbers were provided using a random number generator that is initialized with the same seed [Law and Kelton, 2005]. The integration step for quality evolution was fixed at 30 minutes, since smaller steps did not affect the results. A simulation length of 2,014 days (i.e. ± 5.5 year) was used for the scenario assessment, which was sufficient to obtain stable simulation outcomes. The data gathered during the first 14 days was excluded from the analysis as a warm-up period, which ensured a representative filling of the complete supply chain with fresh produce [Law and Kelton, 2005].

6.6 Results

Section 6.6.1 includes the results of the supply chain scenarios described in section 6.4.3, performed using the chain simulation. A sensitivity analysis on several key parameters is presented in section 6.6.2.

6.6.1 Scenario comparison

Studies of the use of FP (e.g. van Kampen and van Donk [2013]) typically assess what effect FP has on both observed service levels and inventory levels. As product obsolescence and poor product quality are common problems in perishable supply chains, we provided a broader analysis to fully assess the impact of FP. The results of the scenario analysis are shown in Figure 6.4 and Table 6.6.

As shown in Table 6.6, the service level threshold (95 %) was not met in scenario 1, as a result of product waste at the retailer. In addition, the service level for scenario 4 was 0.69 to 0.74 % higher than for scenarios 2 and 3. These differences in service levels were caused by the retailers

Table 6.6: Average scenario performance.

Scenario	Service level (%)	Distributor inventory (% of scenario 1)	Retailer inventory (% of scenario 1)	Quality (-)	Age (days)	Waste (%)
1	94.48	100.0	100.0	6.83	5.03	1.28
2	95.13	89.8	102.0	7.13	4.96	0.07
3	95.11	89.7	102.0	7.25	4.95	0.03
4	95.87	89.7	114.9	7.29	5.03	0.00
5	95.36	89.8	36.5	7.42	4.59	0.00

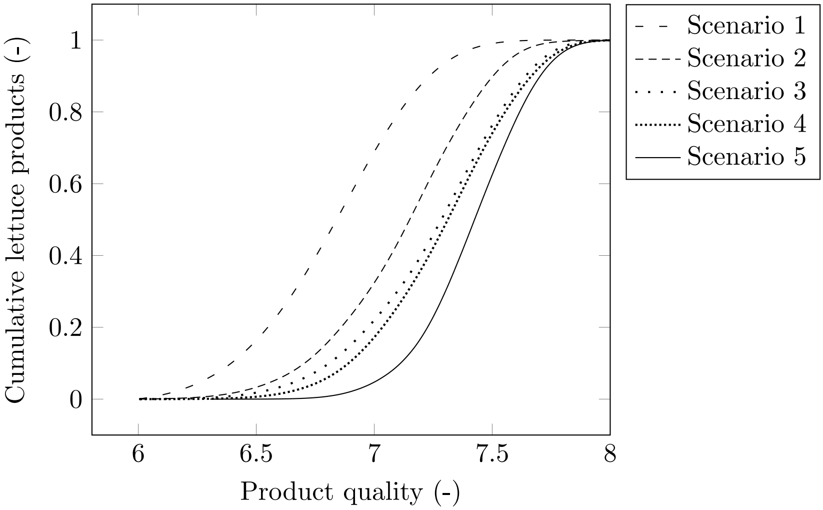


Figure 6.4: Quality distribution of sold lettuce products.

replenishment strategy. In scenarios 1, 2, 3, and 5, the retailer replenished the bagged lettuce inventory once a day, but in scenario 4, they were replenished twice a day. As a result of the integer nature of ordering quantities, the observed service levels were typically higher than the required shelf life.

Two inventory locations were distinguished in the considered supply chain (at the distributor and at the retailer). Inventory levels are measured as the quantity of inventory present at the retailer or distributor at the end of the day, relative to the base scenario. Table 6.6 shows the effect FP had on average inventory levels at both locations. As shown, the distributor inventory levels were significantly lowered (10.2 to 10.3 %) when FP was applied at the distributor (scenarios 2 to 5 versus scenario 1). In addition, Table 6.6 shows that retail inventory levels were increased by 14.9 % for scenario 4 compared to the base scenario, as a result of keeping both an inventory of whole crop and processed fresh-cut lettuce. The retail inventory levels were reduced by 63.5 % for scenario 5 compared with the base scenario. The quantity of required inventory was significantly lower for scenario 5, because FP allowed the retailer to aggregate uncertainty in demand volumes for all end products.

Use of FP reduced the average product age by 1.4, 1.5, and 8.8 % for scenarios 2, 3, and 5 respectively, whereas the average product age of scenario 4 was nearly identical to that of scenario 1. Again, the practice of keeping two types of inventory at the retailer caused the relatively poor performance of scenario 4. However , the differences in product age and product quality decay resulted in a substantial product quality benefit, as shown in Figure 6.4. FP also will reduce the quantity of product waste because poor product quality will ultimately result in product waste (see Table 6.6). As the quality of most sold produce was far above the required minimum quality level (6), the difference in product waste among scenarios 2 to 5 was relatively limited. However, the distribution of product quality in the different scenarios indicates that FP applied towards retail outlets may reduce food waste in case of further delays or temperature disturbances in the supply chain. The following section provides an additional sensitivity analysis to separate the effect of FP from the effect of differences in quality decay rate of whole crop and fresh-cut lettuce.

6.6.2 Sensitivity analysis

From the literature, we know that a number of market characteristics influence the decision for a postponement strategy, such as demand volatility, volume, and product range [Olhager, 2003]. In this section, we describe a test of the sensitivity of the previously presented results for three key parameters that were found to have a large impact on product throughput time and product quality: variation in service level, demand volume, and quality decay properties.

The first parameter is the service level the distributor and retailer employed to determine their order quantity and safety stock (currently 95%). High product availability will improve consumer satisfaction, but keeping large quantities of inventory also may compromise the quality of perishable products. As a result, actors in food supply chains must balance product availability with food quality and waste. To see how variation in service level impacts the effectiveness of FP in perishable supply chains, we assessed performance for different service levels (between 95 % and 99 %). The effect this variation had on food waste is presented in Figure 6.5. Figure 6.5 shows that higher service level requirements increase food waste, and that FP (scenarios 2 to 5) is an effective strategy to limit waste. Therefore, if achieving a high service level is of key importance, FP may be useful to limit product waste in the considered lettuce supply chain.

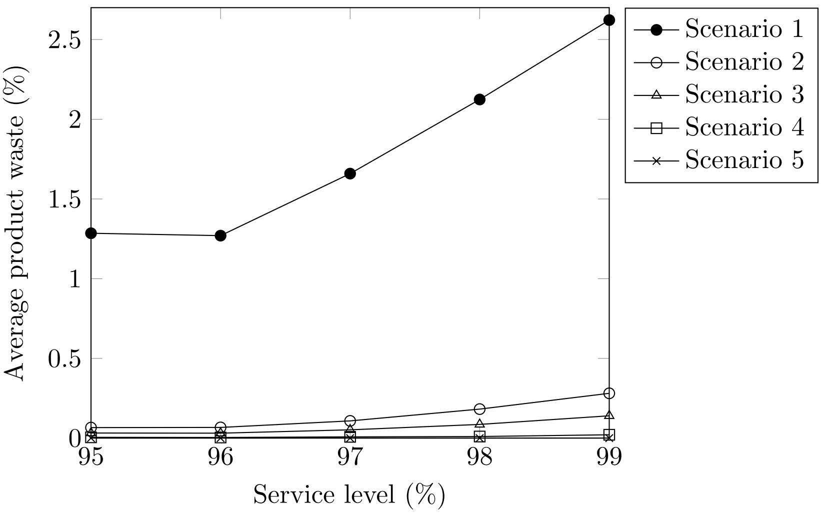
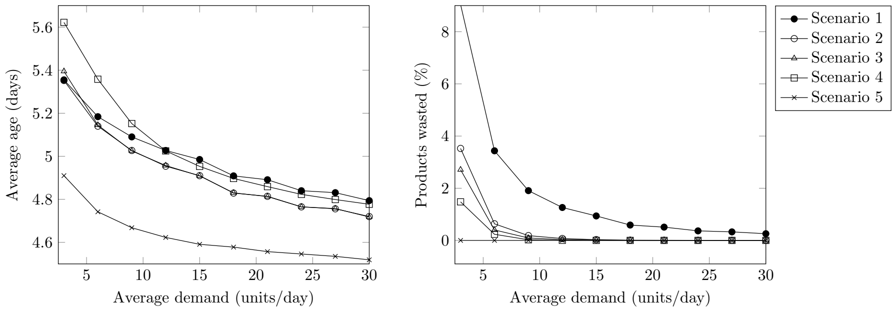


Figure 6.5: Effect of variation in service level on product waste.

Another factor in the effectiveness of postponement strategies is the product volume sold at retail outlets. To assess how product volume affects FP in this lettuce supply chain, average demand for individual end products was varied between 2.5 and 30 units per day at each of the retail outlets. Figure 6.6(a) shows that increasing product demand reduced the throughput time in all scenarios, because the relative quantity of safety stock to hedge against demand variability was reduced. Figure 6.6(b) shows that these reductions in throughput time also reduced food waste, and with the application of FP, food waste reduction decreased as the sales volume increased. Figure 6.6(a) shows that for very low demand levels, the relative performance of scenario 4 was reduced against the base scenario (scenario 1). The double quantity of inventory kept at the retailer (both whole crop lettuce and fresh-cut lettuce) caused this performance reduction. Thus, for very low demand volumes, the relative gain of postponed processing does not outweigh the increase in throughput time resulting from keeping of two types of inventory. The average product age delivered by scenario 5 was superior for the complete range of demand (Figure 6.6(a)), although the reduction in product waste resulting from this was limited for higher



(a) Product age. (b) Product waste.

Figure 6.6: Average product age (a) and waste (b) for varying average demand levels.

Table 6.7: Alternative quality decay properties.

	Scenario number				
	1	2	3	4	5
	Average waste (%)				
Standard	1.28	0.07	0.03	0.00	0.00
High quality demand	11.38	2.41	1.44	0.59	0.00
Identical decay	6.22	5.42	5.26	5.39	2.28
Double decay	8.37	11.06	17.49	20.37	8.95

demand volumes (Figure 6.6(b)).

A third factor that may impact the applicability of FP to perishable supply chains is the rate of quality decay of both processed and unprocessed products, and consumer preferences for product quality. To assess the impact of these factors, we compare the performance of the five scenarios with the performance obtained for three alternative parameter settings. First of all, a situation in which consumers are more critical about the quality of lettuce products is considered (minimum acceptable product quality is 6.5). In the second situation the quality decay model for fresh-cut lettuce is also used for whole crop lettuce (remember that in the normal situation the quality decay of fresh-cut lettuce is faster, see Figure 6.3). In the final set of parameter settings the quality decay rate of whole crop lettuce is doubled and the decay rate of fresh-cut lettuce is kept constant, or in other words, the rate of quality decay of whole crop lettuce is actually higher than that of fresh-cut bagged lettuce. The effect of these changes on average age at point of sale and average waste are shown in Table 6.7.

The results in Table 6.7 clearly indicate that the performance improvements brought by FP will increase if consumers become more demanding regarding the quality of products they buy. From the results presented in Table 6.7, we also can conclude that the rate of quality decay, and more specifically the relation between quality decay rate of both unprocessed and processed lettuce products, has a strong impact on the effectiveness of FP. If quality decay rate of whole crop lettuce is similar to that of processed lettuce, the overall waste levels will go up, and FP will still bring substantial benefits, particularly in scenario 5. If, on the other hand, the quality decay rate of whole crop lettuce is doubled, application of FP will lead to substantial increases in food waste because the keeping quality of whole crop lettuce is much lower. In this case, only scenario 5 will result in a performance comparable to the base scenario.

6.7 Conclusion and discussion

In this case study, the application of FP to a perishable supply chain was examined. Several supply chain design scenarios for an international lettuce supply chain were defined that differed with respect to the position where whole crop lettuce was processed into fresh-cut bagged lettuce. The performance of these supply chain scenarios was assessed using a chain simulation tool. Both the flow of whole crop and fresh cut lettuce, from grower to the retail outlets, were simulated and quality decay was predicted using spoilage models for whole crop and fresh-cut lettuce.

Model results presented in section 6.6.1 indicate that use of FP would improve product quality and reduce product waste in this lettuce supply chain by 1.21 to 1.28 %. This result leads to the conclusion that applying FP to perishable product supply chains may result in an improvement in product quality and reduction of food waste. The observed improvements in this case study may be related to both the application of FP and the more favorable quality decay properties of whole crop lettuce. Application of FP reduced the product throughput time by up to 8.8 %, which is favorable for the quality of perishable products. These results confirm the hypothesis that applying FP in perishable product supply chains may improve the quality of sold products and reduce the quantity of products lost through obsolescence. Please note that implementing FP and relocating processing steps will have a significant impact on the organisation of supply chains, and is likely to have an effect on the efficiency of food supply chains.

The sensitivity of the considered system was tested for changes in service levels, product volume, and quality decay rate, as presented in section 6.6.2. Higher service levels were shown to reduce product waste; therefore, if providing high service levels is important, FP may help to control food waste at acceptable levels. In accordance with earlier findings in the literature, the advantages brought by application of FP are reduced by increases in product volume. This reduces the positive impact of FP on delivered product quality and observed food waste. In addition, we found that for very low demand levels, keeping both generic and dedicated inventory at the retailer (scenario 4) will increase the product throughput time, and make lettuce processing to order (scenario 5) beneficial. These results show that product volume has a strong effect on the benefits of FP. An analysis of the sensitivity of the simulated system to variation in demand for quality features indicated that consumer demand for higher product quality increases the benefits of FP, with waste reductions of up to 11.38 %. This result indicates that application of FP may help supply chain actors to deliver products of premium quality. Simulation results studying the effect of variation in quality decay rate of both unprocessed and processed lettuce indicate that the effectiveness of FP depends on changes in the relationship between quality decay rate of both unprocessed generic products and processed products: If product decay before processing is lower than after processing, favors the application of FP, and vice versa. Although application of FP may reduce the product throughput time, the positive effects this has on product quality and food waste may be annulled or enhanced if the quality decay rate before processing is either lower or higher than that of processed products.

In this case study, we assessed how specific characteristics of food supply chains (i.e. perishability) affect the applicability of FP to food supply chains, which is an area that has not received much attention in the literature [van Kampen and van Donk, 2013]. The presented chain simulation allows practitioners to assess the effect of FP on product waste. In addition, this case study showed how a well-known supply chain strategy may contribute to food waste reduction, which adds to the discussion regarding the most appropriate SC designs for perishable product supply chains. An interesting finding was the effect of lettuce processing at the retail location. The simulation results revealed that keeping a separate inventory of whole crop lettuce and fresh-cut lettuce at the retailer (scenario 4) may actually increase total throughput time at the point of sale, depending on the sales volume. A possible solution to this result would be to process lettuce upon consumer order (scenario 5), although this practice might be difficult to implement within the retailer's operation. Note that this is an exploratory case study on the relation between food waste and application of FP in a perishable product supply chain. Therefore, any implementation costs and the financial viability of FP in perishable supply chains must be assessed in a separate study.

In future research it would be interesting to study the impact of consumer behaviour on FP in more detail, for instance by considering product substitution [Smith and Agrawal, 2000]. Furthermore, it would be interesting to expand the current focus on product quality and food waste to study the effect of FP on food safety by performing a quantitative microbiological risk assessment on different pathogens that may be present on lettuce products.

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Chapter 7
General discussion

Willem A. Rijpkema

"Effective use of product quality information in food supply chain logistics"

PhD Thesis, Wageningen University

7.1 Brief Outline of the Research

Food supply chains characteristically require specific logistics management solutions. Actors in food supply chains have to deal with, among other concerns, seasonality, product perishability, and variability in quantity and quality of produced products. Furthermore, developments such as globalisation and scale intensification complicate supply chain logistics. These complications require logistics management strategies in order to meet consumer expectations. Since advanced product quality information plays a central role in these strategies, this thesis investigates its use in logistics decision making, with the goal of aiding food supply chain decision makers. The main research question that was investigated in this thesis is:

> How can the effectiveness of logistics decision making in food supply chains be improved using advanced product quality information?

Within the scope of two EU-funded research projects (*Q-porkchains* and *Veg-i-Trade*) and in collaboration with industrial partners, four case studies were defined to address the relation between two quality characteristics common in food supply chains (i.e. product quality variability and dynamic product quality), and two types of logistics decisions (i.e. product sourcing and process design). Research questions corresponding to the key gaps in the relevant literature were defined for each case study. Each case study developed quantitative methods for using product quality information by assessing the potential impact of logistics decisions on predefined performance indicators. An overview of the supported decision type, the food quality characteristics and the corresponding chapters can be found in Table 7.1.

Table 7.1: Overview of research design, and chapters.

	Product sourcing Chapter	Process design Chapter
Variability in product quality	3 + 4	2
Dynamic product quality	5	6

In this chapter, the case study findings are summarised and related to the overall research objective. Section 7.2 presents the findings derived from the individual research questions. The integrated findings and case study contributions are discussed in section 7.3. Managerial implications are provided in section 7.4, and suggestions for further research are discussed in section 7.5. Final remarks are given in section 7.6.

7.2 Case study findings

This section presents the main findings of the case studies. For each study, a brief introduction and applied methods are given, after which the associated research question is provided. The research question is followed by the key findings.

Case study 1: Process design for advanced sorting of meat products
This case study, presented in chapter 2, considers the process design of a meat processing company that seeks to add value by exploiting differences in individual product quality and sorting them into consumer segments. Product quality information availability is crucial for this; for this study, using an innovative sensor technology that provides meat quality feature estimates has been investigated. The subject of this study was to investigate how sorting of products for these quality estimates affects efficiency and optimal process design. Process design scenarios are defined that differ with respect to sorting complexity (i.e. whether and to how many segments products are sorted), available product quality information (i.e. no quality information, quality estimates, and perfect quality information) and using temporary product buffers (i.e. products are sorted to small buffers, and processed batch-wise). Product buffers are undesirable for meat products, as they reduce shelf life and require additional labour. A discrete event simulation model has been developed to assess system performance and allow for a detailed analysis of the design scenarios. This model has been used to investigate the following research question:

> RQ1: How can differentiated consumer segments be served efficiently through sorting for more product quality features?

Case study findings reveal that using product buffers is favourable for scenarios with a high processing complexity. Using product buffers increased overall costs by 25% for scenarios with a low sorting complexity (no sorting for advanced product quality features), and reduced overall costs between 3.4% and 16.7% for scenarios where products are sorted to three and five segments respectively. This indicates that use of product quality estimates allows for product segmentation. The effect of using potentially uncertain product quality information on expected customer claim costs was also assessed, indicating that significant performance improvements can be obtained despite uncertainty in quality information.

The simulation allows practitioners facing segmented customer demand to assess the responsiveness and flexibility of supply chain configurations. By combining this insight with data on the added value of products sorted for advanced quality features, both the benefits and drawbacks can be quantified.

Case study 2: Livestock sourcing decisions

This case study, presented in chapters 3 and 4, considers a meat processing company that faces quality feature variation in animals delivered to its slaughterhouses (e.g. weight, meat leanness), which results in fluctuation in both processing performance and final product quality. The meat processor currently transports livestock from farms to the nearest slaughterhouse to minimise transportation costs, and gathers quality information after slaughtering. Since no information on livestock quality delivered by individual farmers is used while making allocation decisions, there is product quality uncertainty on arrival at the slaughterhouse. Reducing this uncertainty may allow decision makers to improve the match between supplied products and end markets.

This study assesses whether uncertainty in livestock received at individual slaughterhouses may be reduced by using product quality information gathered during earlier deliveries. Two stochastic programming models were developed to generate slaughterhouse allocation plans based on product quality information. These models use a scenario-based approach, in which historical farmer delivery data is used to model scenarios for delivery of future product quality. The first model, presented in chapter 3, generates plans that fulfil slaughterhouse quality attribute demands at a predefined service-level while minimising transportation costs. In the models presented in chapter 4, generated allocation plans simultaneously minimise both transportation costs and average expected shortfall from product quality demanded at the slaughterhouse. Algorithms are presented for both models, which can be used to obtain efficient solution sets. This allows the decision makers to assess trade-offs in the relevant performance dimensions. The models are tested on real-world problem instances generated from the processing companys dataset.

Two research questions were investigated in this case study, relating both to applying the presented models (RQ 2A), and using this type of stochastic programming model to obtain efficient solution sets (RQ 2B). We first discuss research question 2A:

RQ2A: Can historical quality delivery data from farmers be used to improve sourcing decisions in food supply chains?

The results presented in chapters 3 and 4 show that historical farmer delivery data can be used to reduce future delivery quality uncertainty. Practitioners facing livestock quality uncertainty may therefore adopt the developed models. Furthermore, the model presented in chapter 3 in particular allows the decision maker to assess trade-offs between transportation costs and slaughterhouse service level. In the chapter 3 results, service-level improvements of up to 44.0 % were found, resulting in transportation cost increases of up to 4.6 %. The chapter 4 results revealed that expected shortfalls were reduced up to 99.4 %, although this resulted in transportation cost increases of up to 33.4 %. The model presented in chapter 4 allows decision makers to balance both transportation costs and average shortfall from demanded carcass qualities. Apart from reducing received livestock uncertainty, the models may be used to assess what effect quality variation may have on transportation costs if a quality-based allocation is used. This reveals the potential benefit processing companies may obtain if farmers manage to reduce product quality variation.

The second research question investigated using this case study is:

RQ2B: How can efficient solutions that provide a trade-off between different performance indicators be obtained using stochastic optimisation?

An important class of decision making problems aims at balancing multiple objectives.Decision making problems merit efficient solutions that balance multiple objectives. This case study considers problems that have a large but finite number of feasible solutions. To support decision making for this problem type, two types of stochastic programming approaches that use scenario-based modelling are presented. The first approach, presented in section 3, incorporates service-level constraints, while the second approach, presented in section 4, incorporates bi-criterion techniques.

The binary nature of service-level constraints (i.e. solutions are either feasible or not depending on the stochastic processes captured by the scenarios) makes the required computational effort to solve this type of problem relatively large. To obtain efficient solution sets for the considered livestock allocation problem, a two-stage heuristic approach was employed. In the first stage, solutions were obtained for the programming model using a relatively small number of scenarios (150 in the presented case study). As this small scenario set may not fully represent the stochastic distribution, the obtained solutions effectiveness was tested using an independent and larger scenario set (5,000 in the presented case study). The implementations and computational experience presented in chapter 3 indicate that trade-offs in multiple performance indicators can be found for practical problems using stochastic programming models that include service-level constraints.

The bi-criterion approaches presented in chapter 4 simultaneously minimise both transportation costs and quality deviations. Two classical bi-criterion approaches exist (i.e. the constraint method and the weighting method), for which a specific implementation is required for this subset of problems. Chapter 4 presents two specific implementations to obtain solution sets that are Pareto-optimal in two performance dimensions. Both approaches balance transportation cost and the average expected livestock quality shortfall. The presented implementations reveal that efficient solutions for bi-criterion problems with a large, but finite set of feasible solutions can be found for real-life problem instances.

The computational experience reveals the computational efficiency of both the service-based approach and the bi-criterion approaches and shows that using service-level constraints tends to result in a higher computational burden compared to the bi-criterion approaches. This will reduce the feasible problem size, or require alternative procedures to obtain feasible solution sets, such as the two-stage approach presented in chapter 3.

Case study 3: Product sourcing in international strawberry supply chains

Case study 3, presented in chapter 5, investigates the supply chain of an international fresh fruit distributor. This distributor struggles with sourcing strawberries internationally when no local supply is available, often resulting in poor product quality and substantial wastage. The distributor sources his strawberries exclusively from Egypt during several months of the year, and ships them using either a slow, but cheap transport mode (i.e. sea and truck), or a faster, but more expensive mode (i.e. plane). The distributor would like to know what sourcing strategy should be employed to optimise product availability while minimising both product waste and overall logistics cost. Two hypotheses were posed: (i) sourcing strategies found in the literature may not suffice in perishable product supply chains; and (ii) robust performance improvements may be achieved in perishable product supply chains by including costs for expected shelflife losses while determining sourcing strategies. These hypotheses were tested by assessing whether an existing dual sourcing strategy called the dual-index order policy supplied perishable products of appropriate quality with acceptable waste levels.

This dual-index policy minimises integral logistics cost for transportation, shortages and inventory keeping. Alternative scenarios were defined to assess whether the obtained policies can be improved. In these scenarios, costs for expected losses in shelf life, obtained using microbiological growth models, were included in the cost parameters used. These extra costs make inventory keeping and slower transportation modes less attractive. The obtained policies performance was examined using a discrete-continuous chain simulation. Shelf-life losses during transport and storage were predicted in this simulation tool using microbiological growth models.

The research question that was investigated in this case study is:

> RQ3: How can advanced product quality information be used to improve product sourcing in perishable product supply chains?

The case study results illustrate that existing sourcing strategies, such as the dual-index policy, may, in fact, result in large amounts of waste and poor product quality if applied to international perishable product supply chains. A methodology presented to integrate costs for expected shelf-life losses while generating sourcing strategies was shown to improve the dual-index order policy for these chains. The case study results show that the sum of cost drivers traditionally used to obtain adopted sourcing strategy order policies (i.e. regular transport costs, expedited transport costs, inventory holding costs, and shortage costs) increased by 23.8 % as a result of including shelf-life loss costs. However, this cost increase is cancelled out by reduced wastage and retailer claim costs, which reduce the overall cost by 43.8 %. These findings indicate that using product quality information in combination with microbiological growth models has the potential to improve perishable product sourcing.

Case study 4: Use of form postponement for food waste reduction

Form postponement (FP) is an important supply chain strategy that correlates processing steps with a realised demand. The aim is to benefit perishable product supply chains by reducing required inventory levels. To investigate this effect, FP was considered in an international supply chain in which lettuce is processed directly after harvesting into a variety of bags that differ in size and composition. As a result, a relatively large quantity of safety stock is required for each stock-keeping unit at both the distributor and retailer. Applying FP to whole crop lettuce may allow the supply chain actors to reduce the safety stock quantity, which may reduce the product throughput time. As both whole crop lettuce and fresh-cut lettuce are subject to quality decay, this may improve point-of-sale quality and reduce waste.

Five supply chain scenarios were defined that differ with respect to the whole crop lettuce processing location and moment. These scenarios are assessed using a discrete-continuous chain simulation tool that simulates a prototype lettuce supply chain by modelling the flow of both unprocessed products (i.e. whole crop lettuce) and processed products (i.e. processed and bagged lettuce). Both unprocessed and processed lettuce quality decay was predicted using spoilage models available from the literature. This approach allows analysing the relation between product perishability and logistics decision making in detail.

The following research question was investigated in this case study:

RQ4: Can form postponement be used to limit food waste and quality decay in food supply chains?

The results of the presented case study reveal that applying FP may reduce waste and improve point-of-sale product quality. The best performance with respect to product quality and age was obtained for a scenario where lettuce is processed to order at the retailer, resulting in a waste reduction of 1.3 % and a product age reduction at the point of sale of 8.8 %.

The simulation revealed that storing both generic and processed lettuce at the retail outlet may bring benefits, but that for either very low or high demand volumes, it will actually increase average product age.

The simulated systems sensitivity was assessed with respect to changes in three key parameters: required service level, product volume and quality decay properties. This revealed that a higher required service level will increase inventory levels throughout the supply chain, which in turn increases the advantage of applying FP. Simulation revealed that FP application benefits are higher for lower demand volumes, although the scenario where the retailer keeps both a stock of whole crop and processed lettuce performed poorly with respect to quality and waste for low demand volumes. Finally, FPs effectiveness at reducing waste and improving product quality was shown to be sensitive for i.) changes in consumer product quality demand (i.e. stricter quality requirements will make application of FP more favourable), and ii.) changes in quality decay properties, in particular the relation between the decay rate before and after processing. A higher quality decay rate after processing will enhance the advantages brought by FP, whereas a lower quality decay rate after processing will make FP less attractive.

7.3 Integrated findings

This thesis investigates the use of product quality information in logistics decision making by developing and applying quantitative decision support models. The overall research objective was to assess how product quality information can be used to support logistics decision making in food supply chains, which is investigated using the following main question:

> How can the effectiveness of logistics decision making in food supply chains be improved using advanced product quality information?

Four case studies are used to investigate the relation between two common food product quality characteristics (product quality variability and dynamic product quality) and two types of logistics decisions (product sourcing and process design). The remainder of this section discusses the integrated findings in food quality management (section 7.3.1), food logistics management (section 7.3.2), and decision support modelling (section 7.3.3).

7.3.1 Food Quality Management

This thesis investigates the impact of two quality characteristics common to food products on logistics decision making, and presents strategies to mitigate this impact using product quality information. These two quality characteristics are product quality variability and decay, which will be discussed separately.

Variability in product quality

The presented food supply chain case studies illustrate that variability is present in a variety of quality attributes. This may be reduced in production, or along the supply chain. The analysis presented in this thesis focuses on strategies to reduce the negative effects of variability along the supply chain. The findings indicate that dealing with variability is difficult due to the lack of accurate and reliable product quality data. Gathering accurate and reliable data to support the livestock allocation decisions investigated in chapters 3 and 4, for example, would imply gathering individual pig data at a large number of farms. Furthermore, food processing plants practical constraints, such as the meat processor investigated in chapter 2, often require gathering product quality information using non-destructive, rapid, low-cost, accurate, and preferably contact-free sensor technology, which may be difficult to achieve. The results presented in chapters 2, 3, and 4, however, indicate that product quality variability may lead to inefficient material usage and poor customer satisfaction. Variability may therefore have a significant performance impact, which creates a need for logistics strategies that reduce the negative effect of variability in product quality. This thesis presents and assesses variability reduction strategies by exploiting uncertain product quality information (see chapters 2, 3, and 4).

Dynamic product quality

Many food products have one or more quality attributes that are subject to the influence of environmental conditions and time. These changes may lead to consumer dissatisfaction, and are responsible for large quantities of waste (e.g. [FAO, 2013a]). The work presented in this thesis illustrates that use of product quality information and predicting the dynamic behaviour of product quality attributes may help decision makers to improve product quality and reduce food waste. Chapters 5 and 6 present two specific logistics management strategies that may reduce the negative effect of dynamic product quality attributes.

This thesis investigated the use of product quality information in logistics decision making in food supply chains, and the presented methods therefore rely on the information availability. This thesis therefore does not directly contribute to the food quality management literature. However, the findings confirm the need for comprehensive equipment and quality management systems, and assess the impact of reliability and accuracy of product quality data. Therefore, the presented work has implications for food quality management, and provides guidelines to assess what added value may be obtained by specific actions.

7.3.2 Food Logistics Management

As mentioned earlier, food logistics management is defined in this thesis as that part of supply chain management that plans, implements and controls the efficient, effective, forward and reverse flow and storage of food products, food services, and related information between the point of origin and the point of consumption. It therefore encompasses a variety of decisions, such as product sourcing, production planning, distribution planning, and planning of return flows. The focus of this thesis is on two types of decisions that have an impact on final product quality: product sourcing and processing design.

Product sourcing

In recent decades, consumers have become increasingly critical with respect to food quality attributes. In addition, year-round demand for fresh products as well as food supply chain globalization have led to an increase in sourcing decision complexity. This thesis presents two case studies that investigate the effectiveness of food supply chain sourcing decisions in this context. The findings of these case studies indicate that ineffective product sourcing may result in a variety of performance deviations (see chapters 3, 4, and 5). Product variability may, for instance, lead to a poor match between supplied and demanded product quality (see chapters 3 and 4). Furthermore, ineffective sourcing in combination with the perishable nature of food products may result in poor product quality, which ultimately leads to food waste (see chapter 5).

Several strategies were found to improve the effectiveness of product sourcing in food supply chains. Chapters 3 and 4 present and assess uncertainty reduction strategies. In addition, a strategy to improve perishable product sourcing is presented and tested in chapter 5. This case study also revealed that employing multiple sourcing modes may be used to mitigate risks of demand uncertainty while reducing stock levels, thereby improving product quality and reducing product waste.

The case study findings demonstrate the importance of flexibility and responsiveness in reducing the negative effect of both product quality variability and dynamic food quality. Quantitative models were found to be a useful tool to aid sourcing decision makers. These models may be used to obtain efficient solutions through optimization procedures (see chapters 3 and 4), or to assess the impact of product sourcing decisions in a supply chain environment through simulation (see chapter 5). The use of discrete continuous chain simulation models, such as those in chapter 5, were shown to allow a detailed analysis of indicators related to both logistics performance and dynamic product properties.

Process design
Food supply chain developments put an increasing demand on the design of food supply chains to be both efficient and flexible. An ineffective process design may result in performance deviations, as demonstrated in the case study presented in chapter 2. Furthermore, low levels of flexibility in perishable product supply chains may result in poor product quality, and ultimately product waste (see chapter 6). A process redesign may accommodate efficient sorting to satisfy segmented consumers, as demonstrated in chapter 2. Furthermore, supply chain strategies such as form postponement may be used to improve flexibility and reduce product waste (see chapter 6).

The findings of this thesis reveal that effective use of product quality information in food supply chains has the potential to improve food supply chain performance. This may, however, require a more flexible and responsive process design. In particular, the case studies reveal that inventory points should be used tactfully to maintain efficiency while delivering appropriate product quality. The effectiveness of quantitative decision support models, in particular simulation, in assessing the performance of process design scenarios was also demonstrated.

7.3.3 Decision support models

Quantitative decision support models were developed to investigate the effectiveness of strategies for using product quality information in a supply chain context. In particular, optimization models and simulations were applied. The case studies indicate that the specific characteristics of food supply chains often complicate analytical approaches. This provides an opportunity for using heuristics or simulations. Chapters 2, 3, 4, 5, and 6 present several of these approaches applied on practical case studies.

First, optimization models were developed. Applying chance constraints for uncertainty reduction in a practical case is investigated in chapters 3 and 4. Handling of chance constraints is a difficult item in optimization models. Chapter 3 presents a new two-stage approach to deal with chance constraints for problems with an integer feasible area. Chapter 4 uses several classical ideas of the constraint method and the weighted sum method in bi-criterion decision making for a practical problem with an integer feasible area. The developed stochastic programming models demonstrate the feasibility of such approaches to support decisions and reduce inherent variability or uncertainty common in food product quality.

The second type of developed model was simulations. Simulation flexibility allows for the detailed analysis of supply chain scenarios that include realistic parameters and assumptions, as shown in chapters 2, 5, and 6. The simulation presented in chapter 2 includes a detailed analysis of process design scenarios with respect to a set of predefined key performance indicators. The supply chain simulations in chapters 5 and 6 include both discrete (i.e. product and information flows) and continuous (i.e. dynamic product properties) processes, and can be used to investigate the relation between logistics decisions and dynamic product quality attributes. The case studies demonstrate the viability of discrete-continuous simulation models to assess the impact of logistics decisions in a complex perishable supply chain environment.

The findings of this thesis show that both simulation and optimization models may be used to support logistics decision making and exploit product quality information. These decision support models can provide insight into performance indicator trade-offs. For simulations, this can be done by comparing the different user-defined logistics scenarios. When optimization procedures are used, insight into performance trade-offs may be obtained by using algorithms such as those presented in chapters 3 and 4.

7.4 Managerial implications

Food supply chains are characterised by a number of common characteristics and developments that impact logistics decision making, such as variety in delivered product quality (see chapters 2, 3 and 4). Furthermore, supply chain developments have resulted in large volumes of food being transported over long distances (see chapters 5 and 6), often resulting in poor product quality and waste. Logistics management strategies that integrate information on relevant product quality attributes are therefore needed to satisfy consumers. Having information on the remaining product shelf life may, for example, allow a decision maker to improve logistics decisions, which might reduce waste.

This thesis shows that three steps are useful for integrating product quality information in logistics management strategies. First of all, a detailed supply chain analysis is needed that investigates the different supply chain entities, the adopted market channels, the distribution network and, ultimately, the consumers and their product attribute preferences. The objective should be to provide consumers with food products of a consistent and appropriate quality at the right place, price, and time, as this will lead to durable consumer value. By doing so, food supply chain actors may differentiate their products from basic commodity goods.

After finalising the supply chain analysis, the information source that has most potential to bring performance improvements should be identified using a number of questions, such as

- What is the accuracy of the information?
- What is the cost of acquiring this information?
- Which decisions can be supported using this information?
- What performance improvement can be obtained using this information?

The third step is to determine what method or strategy can be used to support logistics decisions using this information source. The complexity of supply chain decision making complicates the prediction of the impact of logistics decisions, or to determine what will provide the best overall performance. There may, for example, be product quality information uncertainty (see chapters 2, 3 and 4), or a logistics decision may have broader implications for supply chain efficiency (see chapters 2 to 6). The thesis reveals that quantitative decision support models can be used to assess both advantages and disadvantages brought by an alternative supply chain design. These quantitative models should not merely provide a solution, but should provide insight and support by finding efficient solutions (i.e. those solutions that are at least near-optimal), and providing insight into the trade-offs in different performance dimensions resulting from logistics decisions.

The presented case studies illustrate that a flexible and responsive supply chain design is required to reduce the negative effect of product variability and quality decay. This flexibility determines the freedom supply chain actors have to exploit product quality information and optimise the match between supplied and demanded product quality. Flexibility and responsiveness may be adapted at different decision levels. Using product buffers was shown to be beneficial while sorting individual products (see chapter 2). Implementing more responsive sourcing strategies also proved beneficial (see chapter 5). The case studies indicate that increasing responsiveness and flexibility typically comes at the expense of other performance dimensions. In the investigated studies, concessions were made with respect to throughput time resulting from product buffers (chapter 2), transportation cost (chapters 3 and 4) and expedited transportation costs (chapter 5). These findings demonstrate the importance of obtaining insight into trade-offs resulting from information-based supply chain performance improvement, and illustrate how quantitative decision support models may be used for support.

7.5 Suggestions for further research

This thesis presents four case studies that investigate the relation between two quality characteristics commonly observed in food supply chains (product quality variability and dynamic product quality) and two types of logistics decisions (product sourcing and process design). This, naturally, limits the broader case study finding validity toward other food supply chains and quality characteristics. This section discusses a number of research directions that could expand on the presented work. This is, however, not an exhaustive overview of all limitations and areas for further research. For further research suggestions related to the individual case studies, the reader is referred to the respective chapters.

The research presented in this thesis is part of a larger research framework aiming to develop decision support models for food supply chains. The nature of food supply chains and food products calls for the integration of Logistics Management and Operations Research techniques with both life-science domains (e.g. food sciences, plant sciences, environmental sciences) and advanced technology (e.g. ICT and process technology). Developments in both food supply chains and technology change food supply chain logistics requirements in a number of ways, which calls for a redesign of logistics networks and the development of logistics control concepts [van der Vorst, 2011]. This thesis demonstrates the potential that use of product quality information has in this environment, but there is still a large potential for future research.

Logistics network design for perishable products is changing rapidly, and distribution networks increasingly rely on multi-modality and joint consolidated distribution hubs, whereas consumers demand flexible logistics and home delivery services. These developments take place in the face of globalization, increased demand for sustainable production and distribution systems, and climate changes that may threaten the quality, quantity and safety of food products. Although interesting work has been done in this field (e.g. Soysal et al. [2014], the *Veg-i-Trade* project), there is still ample opportunity for improved decision making using product quality information.

Developments in food supply chain product (e.g. GMO, 3D printing), process (e.g. automation, modified atmosphere packaging), and information technology also create a potential for future research. Particularly the so-called techno-managerial approach [Luning and Marcelis, 2009], whereby technological developments and logistics decision making are integrated, provides options for improved logistics decision making. The viability of integrating innovative technology and use of quality information to support logistics decision making in food supply chains was demonstrated in this thesis. However, this integration also allows for pro-active control strategies, captured in the quality controlled logistics framework presented by van der Vorst et al. [2011]. Quality controlled logistics encapsulates the application of a number of innovative logistics control strategies, such as orchestration or virtualisation of logistics networks. The relevance of developments in this direction is acknowledged by logistics institutes (e.g. Dinalog), industrial partners (e.g. FloraHolland), and several recent literature contributions (e.g. de Keizer et al. [2014]). Despite this attention there is a still a large potential for improvement in food supply chains through pro-active control strategies.

The presented work demonstrates the effectiveness of quantitative decision support techniques in food supply chains, particularly use of discrete continuous event simulation and chance-constraints. Use of discrete-continuous event simulation was shown to allow for detailed impact assessment of logistics decisions in relation to food quality (see chapter 5 and 6). Despite the potential of this technique, its application in this field is still relatively limited. The use of chance-constraints for decision support in the face of uncertainty was demonstrated in a practical setting in chapter 3 and 4. In future research it would be interesting to assess other applications of similar techniques in practical case studies. Another interesting direction for future research is the application of other model types to support decision making in food supply chains. Recent examples include Govindan et al. [2013], who used a hybrid approach that allow decision makers to find near-optimal solutions despite complicating characteristics often present in food supply chains.

7.6 Final Remark

The work presented in this thesis provides insight in the effective use of product quality information in food supply chain logistics. By presenting this research, I hope to inspire fellow researchers to continue the journey toward developing strategies for more effective logistics decision making in food supply chains. Furthermore, I hope that the presented work is useful for practitioners, and the presented examples and guidelines may help them to improve food supply chain logistics decision making.

Summary

Food supply chains have inherent characteristics, such as product quality variability and decay, that affect logistics decision making. In addition, food supply chain organization and control has changed significantly in the past decades under the influence of a variety of factors, such as scale intensification, globalization, and consumer requirement changes. These combined characteristics and developments frequently lead to supply chain problems, such as product waste, product quality problems, and high logistics costs. Recent ICT developments have created the opportunity to gather, process, and communicate more information to support logistics decision making. This provides opportunities to better deal with food supply chain challenges, realize performance improvements, and add extra value by differentiating products. Realizing these advantages will require developing effective logistics management strategies that ensure the supply of products of appropriate quality in a cost-effective way. The use of product quality information is central in these strategies, as many challenges in food supply chains relate to product quality. The objective of this thesis was therefore to assess how value may be added in food supply chains through using product quality information in logistics decision making. This objective is captured in the following central research question:

> How can the effectiveness of logistics decision making in food supply chains be improved using advanced product quality information?

This research question is investigated using four case studies: two in the context of the *Q-porkchains* project (i.e. in pork supply chains), and two in the context of the *Veg-i-Trade* project (i.e. in fruit- and vegetable supply chains). The focus of this thesis is on the relation between two quality characteristics commonly observed in food supply chains (product quality variability and dynamic product quality) and two types of logistics decisions (product sourcing and process design). In each case study, improvement opportunities were identified, and strategies were formulated. The impact of these strategies has been assessed by developing quantitative models; validity is ensured by collaborating with industrial partners.

Chapter 1 provides a thesis introduction, along with a description of inherent characteristics of, and developments in, food supply chains. An

introduction to food supply chain management is given, as well as a description of the *Q-porkchains* and *Veg-i-Trade*. Finally, a research statement and questions are provided.

Case study 1: Process design for advanced sorting of meat products
The first case study, presented in chapter 2, considers the process design of a meat processing company that seeks to add value by sorting for a quality feature. The relation between product sorting, processing efficiency, and process design is investigated using a discrete event simulation model. This model assesses process design scenarios of varying complexity (i.e. sorting to 1, 3, or 5 market segments), available product quality information (i.e. no information, estimates, or perfect information) and the use of temporary product buffers (i.e. products are directly processed or sorted to small buffers, and processed batch-wise).

Case studies reveal that using product buffers increased overall costs by 25% for scenarios without advanced product sorting, whereas overall cost reductions between 3.4% and 16.7% were observed while sorting to three and five segments, respectively. Furthermore, findings revealed that expected customer claim costs could be reduced despite use of of potentially uncertain product quality information. The simulation allows practitioners facing segmented customer demand to assess which scenario offers the best trade-off between benefits and drawbacks resulting from efforts to improve responsiveness and flexibility.

Case study 2: Livestock sourcing decisions
The second case study, presented in chapters 3 and 4, considers a meat processing company that faces quality feature variation in animals delivered to its slaughterhouses (e.g. weight, meat leanness), resulting in fluctuation in processing performance and final product quality. As no information is available on livestock quality that individual farmers may deliver, there is uncertainty in product quality slaughterhouses will receive, which may result in a mismatch between supplied and demanded product quality. This study investigates whether product quality information gathered during earlier farmer deliveries can be used to reduce this uncertainty. Two stochastic programming models that use scenario based-modelling were developed to generate slaughterhouse allocation plans based on this historical product quality information. The presented implementations reveal that historical farmer delivery data can be used to reduce uncertainty in supplied

product quality and hence improve processing performance.

The model presented in chapter 3 employs service-level constraints on delivered product quality while generating allocation plans with minimized transportation costs. A two-stage heuristic approach is presented to obtain efficient solution sets. In stage one, solutions are obtained using a relatively small number of scenarios, and the effectiveness of these solutions is tested in the second stage using an independent and larger scenario set. Service-level improvements of up to 44.0 % were found, resulting in transportation cost increases of up to 4.6 %.

Chapter 4 presents two algorithms to obtain solution sets for the presented livestock allocation problem. These algorithms use bi-criterion approaches to simultaneously minimize both transportation costs and average expected shortfall from demanded product quality. Implementing these algorithms revealed that the expected shortfall could be reduced up to 99.4 %, resulting in transportation cost increases of up to 33.4 %.

Case study 3: Product sourcing in international strawberry supply chains
Case study 3 investigates sourcing strategy effectiveness at an international strawberry distributor that faces frequent product quality problems and substantial wastage. The distributor sources Egyptian strawberries using either a slow, but cheap transport mode (i.e. sea and truck), or a faster, but more expensive mode (i.e. plane). The use of an existing dual sourcing strategy called the dual-index order policy is considered to test whether i.) sourcing strategies found in the literature are effective in perishable product supply chains, and ii.) robust performance improvements may be achieved in perishable product supply chains by including costs for expected shelf-life losses while determining sourcing strategies. Sourcing strategies are obtained using cost parameters both with and without costs for expected shelf-life losses. The performance of the obtained policies was examined using a discrete-continuous chain simulation that includes microbiological growth models to predict quality decay.

Simulation results reveal that the standard cost parameters resulted in substantial product waste. Using parameters that included cost for expected shelf-life losses increased the cost drivers traditionally used to obtain policies by 23.8 % (i.e. regular transport costs, expedited transport costs, inventory holding costs, and shortage costs). However, this cost increase is canceled out by reductions in waste and expected retailer claims for poor product quality, which reduced overall cost by 43.8 %. This indicates that including costs for expected shelf-life losses may improve effectiveness of product sourcing in perishable product supply chains.

Case study 4: Use of form postponement for food waste reduction
Form postponement (FP) is a supply chain strategy that delays processing steps until a demand is realized. As FP is known to reduce inventory levels, it is considered for an international lettuce supply chain that struggles with effective product sourcing. The distributor currently sources lettuce that is processed into a variety of end products directly after harvesting, but considers sourcing whole crop lettuce instead to reduce the safety stock levels throughout the supply chain.

Scenarios are defined that differ with respect to the lettuce processing location and moment, and these scenarios are assessed using a discrete-continuous chain simulation that includes quality decay models for both whole crop and processed lettuce. The analysis revealed that FP reduced point-of-sale waste (up to 1.3 %) and product age (up to 8.8 %), while improving point-of-sale product quality. Furthermore, model sensitivity for three key parameters is assessed: required service level, product volume, and quality decay properties.

Integrated findings
The impact of two common food product quality characteristics on logistics decision making are investigated: product quality variability and decay. Findings demonstrate that

- logistics decisions frequently have to be taken using uncertain product quality information, as acquiring reliable data is often impossible,
- the impact of product quality variability or dynamic product quality may be reduced using logistics strategies that exploit uncertain product quality information,
- decision makers may improve improve logistics decisions and reduce food waste by using product quality information and predicting the dynamic behavior of relevant attributes,
- comprehensive equipment and quality management systems are required to obtain suitable product quality information,
- quantitative decision support models can used to assess the impact of reliability and accuracy of product quality data.

Two types of food logistics management decisions that have an impact on final product quality are investigated: product sourcing and processing design. Findings demonstrate that:

- effective use of information on variable and dynamic food product quality properties in logistics decision making can improve food supply chain performance,
- a flexible and responsive supply chain design reduces the impact of product quality variability and quality decay in food supply chains,
- inventory points should be used tactfully to maintain processing efficiency while delivering products of appropriate quality,
- quantitative decision support models can aid food supply chain decision makers in both sourcing and process design decisions.

This thesis presents quantitative decision support models that were used to investigate the effectiveness of strategies for use of product quality information in a complex supply chain context. In particular, optimization models and simulations were applied. Chapters 3 and 4 demonstrate the application of chance constraints for uncertainty reduction in a practical case. Chapter 3 presents a new two-stage approach to deal with chance constraints for problems with an integer feasible area, whereas classical ideas from bi-criterion decision making are used in chapter 4 to support a practical problem with an integer feasible area. Simulation flexibility was used in chapters 2, 5, and 6 to analyze supply chain scenarios that included realistic parameters, assumptions, and quality decay models.

Managerial implications

This research investigated the integration of relevant product quality attribute information in logistics decision making in food supply chains, with the aim of improving overall performance and consumer satisfaction. Three steps were identified to aid decision makers, being i.) perform a detailed supply chain analysis, ii.) identify what information source has most potential for improvements, and iii.) determine what method or strategy can be used to support logistics decisions using this information source, supported using quantitative decision support models.

The presented case studies demonstrate that supply chain flexibility and responsiveness is required to reduce the impact of product variability and quality decay. Increasing responsiveness and flexibility typically comes at the expense of other performance dimensions, and obtaining insight into trade-offs resulting from information-based supply chain performance improvement strategies is therefore important. Optimization and simulation techniques were shown to be effective in gaining this insight.

Suggestions for further research
The case studies presented in this thesis reveal the potential that use of product quality information has in food supply chain strategies, supported using quantitative simulation and optimization techniques. There is, however, still a need for further strategy developments in food supply chains, for instance by developing pro-active logistics control strategies. Furthermore, the use of quality predictive models in simulation tools, or the use of hybrid models, is expected to see more application in the future.

This thesis demonstrates the potential of effective use of product quality information in food supply chain logistics. I hope that researchers will build on the material presented in this thesis, and continue the journey toward developing more effective food supply chain logistics.

Samenvatting

Voedselketens hebben specifieke kenmerken, zoals variabiliteit in productkwaliteit en bederfelijkheid van producten, die de logistieke beslissingen van actoren in de keten beïnvloeden. Daarnaast is de logistieke besluitvorming in deze ketens in de afgelopen decennia sterk veranderd door ontwikkelingen zoals schaalvergroting, globalisering en veranderende consumentenvraag. De combinatie van de kenmerken en ontwikkelingen leiden momenteel vaak tot problemen in voedselketens, zoals voedselverspilling, klantontevredenheid over productkwaliteit en hoge logistieke kosten. Recente ontwikkelingen op het gebied van informatie- en communicatietechnologie (ICT) bieden de mogelijkheid de logistieke besluitvorming te ondersteunen door meer informatie over producten, processen en markten te verzamelen, te verwerken en te communiceren. Daardoor kunnen problemen in voedselketens worden opgelost, prestaties worden verbeterd, en kan door productdifferentiatie extra marktwaarde worden gecreëerd. Om dit te realiseren moeten logistieke strategieën worden ontwikkeld die de kosteneffectieve levering van producten van de juiste kwaliteit waarborgen. Aangezien veel problemen in voedselketens gerelateerd zijn aan productkwaliteit speelt het gebruik van informatie over de kwaliteit van producten een centrale rol in deze strategieën. Dit proefschrift sluit hierbij aan door te onderzoeken hoe toegevoegde waarde kan worden gecreëerd in voedselketens door het gebruik van informatie over de productkwaliteit in logistieke besluitvorming. Deze doelstelling is vastgelegd in de volgende centrale onderzoeksvraag:

> Hoe kan de effectiviteit van logistieke besluitvorming in voedselketens worden verbeterd door gebruik te maken van geavanceerde productkwaliteitsinformatie?

Deze onderzoeksvraag is onderzocht in vier studies: twee binnen het *Q-PorkChains* project (in de vleesverwerkende keten) en twee in het kader van het *Veg-I-Trade* project (in groente- en fruitketens). De focus van dit proefschrift ligt op de relatie tussen twee kwaliteitskenmerken die in veel voedselketens voorkomen (variabiliteit in productkwaliteit en dynamische productkwaliteit) en twee typen logistieke beslissingen (aanvoerstrategie en procesontwerp). In de verschillende studies zijn verbetermogelijkheden

geïdentificeerd en logistieke strategieën geformuleerd. Om de effectiviteit van deze strategieën te analyseren zijn kwantitatieve modellen ontwikkeld; de validiteit van de studies is gewaarborgd door samenwerking met industriële partijen. Hoofdstuk 1 geeft een inleiding tot dit proefschrift, gevolgd door een beschrijving van inherente kenmerken van en ontwikkelingen bij voedselketens. Daarnaast wordt een inleiding gegeven in logistiek ketenmanagement in voedselketens, en zijn de *Q-PorkChains* en *Veg-i-Trade* projecten beschreven. Tot slot worden het onderzoeksdoel en de onderzoeksvragen gegeven.

Studie 1: Procesontwerp voor geavanceerde sortering van vleesproducten
In de eerste studie, beschreven in hoofdstuk 2, is het procesontwerp van een vleesverwerkend bedrijf bestudeerd dat extra waarde aan zijn producten wil toevoegen door te sorteren op kwaliteitskarakteristieken van het vlees. De relatie tussen productsortering, verwerkingsefficiëntie en het procesontwerp is onderzocht met behulp van een *discrete event* simulatiemodel. Dit model is gebruikt om scenarios te analyseren die verschillen in complexiteit (sorteren naar 1, 3 of 5 marktsegmenten), beschikbaarheid van kwaliteitsinformatie (geen informatie, schattingen, of perfecte informatie) en het gebruik van tijdelijke productbuffers (producten worden direct verwerkt of tijdelijk opgeslagen en per partij verwerkt) .

De resultaten van deze studie laten zien dat het gebruik van productbuffers leidt tot een stijging van 25 % in de totale kosten bij scenarios waar geen geavanceerde productsortering wordt toegepast, terwijl kostenbesparingen tussen 3,4 en 16,7 % werden waargenomen bij sortering naar drie en vijf marktsegmenten. Daarnaast bleken verwachte kosten voor levering van producten met een afwijkende kwaliteit te kunnen worden gereduceerd door schattingen van productkwaliteit te gebruiken. Het ontwikkelde simulatiemodel maakt het dan ook mogelijk de voor- en nadelen van een procesontwerp te kwantificeren. Dit faciliteert het maken van een rationele keuze voor het meest geschikte procesontwerp. Hiermee kunnen beslissingen worden ondersteund in voedselverwerkende bedrijven die geconfronteerd worden met een gesegmenteerd klantvraag.

Studie 2: Aanvoerplanning van slachthuizen
In de tweede studie, gepresenteerd in hoofdstuk 3 en 4, is een vleesverwerkend bedrijf bestudeerd dat te maken heeft met variatie in productkwaliteit van aangeleverd levend vee (zoals slachtgewicht en vetpercentage).

Doordat de kwaliteitseigenschappen van vee aangeleverd door individuele veehouders niet op voorhand bekend zijn, is er onzekerheid over de productkwaliteit die slachthuizen ontvangen. Deze onzekerheid kan leiden tot een verschil tussen de beschikbare en gevraagde productkwaliteit, wat zowel de verwerkingsefficiëntie als de kwaliteit van het eindproduct negatief beïnvloedt. In deze studie is onderzocht of kwaliteitsinformatie verzameld na slachting van eerder geleverd vee kan worden gebruikt om deze onzekerheid te verminderen. Om een kwaliteitsgestuurde aanvoerplanning van slachthuizen te genereren zijn twee stochastische programmeringsmodellen ontwikkeld die gebruik maken van historische leverdata in een *scenario-based* modellering. De toepassing van deze modellen laat zien dat onzekerheid in geleverde productkwaliteit kan worden verminderd door gebruik van historische gegevens. Dit vermindert de discrepantie tussen de aangevoerde en gevraagde productkwaliteit.

Het in hoofdstuk 3 beschreven model minimaliseert transportkosten terwijl er tegelijkertijd beperkingen worden gezet op het service-niveau van geleverde productkwaliteit. Efficiënte oplossingsverzamelingen worden verkregen met behulp van een tweetraps heuristische benadering. In de eerste fase worden oplossingen verkregen met behulp van een relatief klein aantal scenario's, terwijl de effectiviteit van deze oplossingen in de tweede fase wordt getest met behulp van een onafhankelijke en grotere set scenarios. De toepassing van dit model liet zien dat het service-niveau tot 44,0 % kan worden verbeterd tegen een stijging in transportkosten van 4.6 %. Hoofdstuk 4 presenteert twee algoritmen om oplossingsverzamelingen voor het voornoemde allocatieprobleem te vinden. Deze algoritmen zijn gebaseerd op *bi-criterium* technieken, waarbij zowel transportkosten als het verwachte tekort aan productkwaliteit worden geminimaliseerd. De toepassing van deze algoritmen laat zien dat de verwachte tekorten tot 99,4 % kunnen worden gereduceerd tegen een stijging in transportkosten van 33.4 %.

Studie 3: Aanvoerstrategiëen in internationale aardbeienketens

De derde studie onderzoekt aanvoerstrategieën bij een internationaal opererende distributeur van aardbeien. Deze distributeur ervaart met regelmaat kwaliteitsproblemen, wat leidt tot voedselverspilling en ontevreden klanten. In de periode dat de distributeur enkel Egyptische aardbeien distribueert kan hij deze op twee manieren laten vervoeren: langzaam en goedkoop (via boot en vrachtwagen), of sneller maar duurder (via vliegtuig). Een bestaande duale aanvoerstrategie, genaamd de *dual-index* bestelprocedure, is gebruikt om te testen of: i.) bestaande aanvoerstrategieën effectief zijn wanneer ze worden toegepast bij ketens met bederfelijke producten, en ii .) prestatieverbeteringen kunnen worden bereikt bij ketens met bederfelijke producten wanneer kosten voor verwachte verliezen in houdbaarheid worden meegenomen bij het bepalen van bestelprocedures. Deze bestelprocedures worden verkregen door waarden van kostenparameters met en zonder kosten voor verwachte houdbaarheidsverliezen te gebruiken. De effectiviteit van de verkregen bestelprocedures is onderzocht met behulp van een *discrete event* ketensimulatiemodel. Om het kwaliteitsverloop van bederfelijke producten onder specifieke omstandigheden te voorspellen zijn microbiologische groeimodellen in dit simulatiemodel geïmplementeerd.

De simulatieresultaten laten zien dat het gebruik van kostenparameters waarin verliezen in houdbaarheid niet zijn meegenomen leidt tot aanzienlijke voedselverspilling. Het gebruik van parameterwaarden die kosten omvatten voor te verwachten houdbaarheidsverliezen leidt tot een verhoging van de traditionele kostenposten (transportkosten, voorraadkosten en kosten voor tekorten). Deze kostenstijging werd in de gesimuleerde keten echter tenietgedaan door een afname van de voedselverspilling en andere kosten gerelateerd aan lage productkwaliteit, wat een daling van totale kosten van 43,8

Studie 4: Gebruik van form postponement bij het reduceren van voedselverspilling

Form postponement (FP) is een ketenstrategie waarbij verwerkingsstappen worden uitgesteld totdat een klantvraag is gerealiseerd. De toepassing van FP, dat gebruikt wordt om voorraadniveaus te reduceren, is onderzocht bij een internationale sla-keten waar productbederf voor problemen zorgt. De distributeur van deze keten laat zijn sla op dit moment direct na de oogst verwerken tot een scala van eindproducten. Er wordt nu overwogen om onverwerkte kropsla in te kopen en op een later punt te verwerken om zo de totale benodigde voorraad in de keten te reduceren.

Om het effect van FP in deze slaketen te analyseren zijn scenarios gedefinieerd die verschillen in locatie en tijdstip van het verwerken van de sla. De effectiviteit van deze scenario's is beoordeeld met behulp van een *discreet-continu* ketensimulatiemodel dat kwaliteitsverloopmodellen van zowel kropsla als versneden en verpakte sla bevat. De analyse toont aan dat FP in deze sla-keten leidt tot een afname van zowel de voedselverspilling (tot 1,3 %) als de productleeftijd bij verkoop (tot 8.8 %), terwijl de productkwaliteit verbetert. Hiernaast is de gevoeligheid van FP voor drie belangrijke parameters onderzocht: vereist serviceniveau, productvolume en kwaliteitsverloop.

Geïntegreerde bevindingen
Dit proefschrift bestudeert de invloed van twee veel in voedingsmiddelenketens voorkomende kenmerken op logistieke besluitvorming: variabiliteit in en afname van productkwaliteit. Dit onderzoek toont aan dat

- logistieke beslissingen vaak moeten worden genomen op basis van onzekere productkwaliteitsinformatie, omdat het verwerven van betrouwbare kwaliteitsinformatie in veel gevallen niet mogelijk is,
- de ongewenste effecten van variabiliteit in productkwaliteit en dynamische producteigenschappen kunnen worden gereduceerd door gebruik van logistieke strategieën die onzekere productkwaliteitsinformatie benutten,
- actoren kunnen logistieke beslissingen verbeteren en voedselverspilling reduceren door effectief gebruik te maken van productinformatie en door verandering in kwaliteitskenmerken te voorspellen,
- geavanceerde technologie en kwaliteitsmanagementsystemen zijn nodig om geschikte productkwaliteitsinformatie te verkrijgen,
- kwantitatieve beslissingsondersteunende modellen kunnen worden gebruikt om de invloed van betrouwbaarheid en nauwkeurigheid van productkwaliteitsinformatie te beoordelen.

Twee typen beslissingen die productkwaliteit in voedselketens benvloeden zijn onderzocht: de aanvoerstrategie en het procesontwerp. De resultaten laten zien dat:

- effectief gebruik van informatie over variabele en dynamische productkwaliteit in logistieke besluitvorming kan prestaties in voedselketens verbeteren,
- een flexibel en responsief ketenontwerp kan het effect van variabiliteit in en verval van productkwaliteit in voedselketens verminderen,
- het gebruik van voorraadpunten kan bijdragen aan het behoud van verwerkingsefficiëntie bij het bedienen van gedifferentieerde markten,
- kwantitatieve beslissingsondersteunende modellen kunnen worden gebruikt om beslissingen in voedselketens te ondersteunen, zowel bij het bepalen van de te volgen aanvoerstrategie als bij het kiezen van het optimale procesontwerp.

Dit proefschrift presenteert kwantitatieve beslissingsondersteunende modellen, in het bijzonder optimalisatie en simulatie, om de doeltreffendheid van strategieën voor gebruik van productkwaliteitsinformatie in een ketenperspectief te analyseren. In hoofdstuk 3 en 4 wordt een optimalisatiemodel met kansvoorwaarden gepresenteerd om onzekerheid in een praktijkprobleem te reduceren. In hoofdstuk 3 wordt een methode gepresenteerd om in twee fasen om te gaan met service-niveau beperkingen voor problemen met een geheeltallig toegelaten gebied. Hoofdstuk 4 presenteert een aanpak waarbij klassieke ideen van bi-criterium besluitvorming worden gebruikt om een praktisch probleem met een geheeltallig toegelaten gebied te ondersteunen. In hoofdstuk 2, 5 en 6 is simulatie gebruikt om ketenscenarios met realistische parameters, aannames en kwaliteitsverloopmodellen te analyseren.

Implicaties van dit onderzoek

In dit onderzoek is het gebruik van informatie over relevante productkwaliteitsattributen in logistieke besluitvorming bestudeerd, met als doel prestaties en klanttevredenheid te verbeteren. Drie stappen om besluitvorming te ondersteunen werden geïdentificeerd, zijnde i.) uitvoeren van een gedetailleerde ketenanalyse, ii.) identificeren van de informatiebron met het meeste potentie voor verbetering, en iii.) bepalen van een methode of strategie om deze informatiebron te gebruiken bij het ondersteunen van logistieke besluitvorming, gebruik makend van kwantitatieve modellen.

De gepresenteerde studies tonen het belang van flexibiliteit en responsiviteit in ketens bij het reduceren van de gevolgen van productvariabiliteit en kwaliteitsverloop. Het verhogen van responsiviteit en flexibiliteit gaat echter meestal ten koste van andere prestatie-indicatoren, en daarom is het belangrijk inzicht te verkrijgen in zowel voor- als nadelen van strategiën voor gebruik van productinformatie. De gepresenteerde studies laten zien dat optimalisatie- en simulatietechnieken hiervoor een effectief middel zijn.

Suggesties voor verder onderzoek

De in dit proefschrift gepresenteerde studies tonen de potentie van strategieën voor gebruik van kwaliteitsinformatie in voedselketens, en laten zien hoe deze strategiën ondersteund kunnen worden door kwantitatieve simulatie- en optimalisatietechnieken. Er is echter behoefte aan meer strategin die aansluiten bij de specificeke karakteristieken van voedselketens, bijvoorbeeld door pro-actieve logistieke strategieën te ontwikkelen die gebruik maken van continu verzamelde temperatuur- of kwaliteitsdata. Daarnaast wordt verwacht dat er in de toekomst meer gebruik zal worden gemaakt van ketensimulaties met kwaliteitsvoorspellende modellen, of het gebruik van hybride modellen.

Dit proefschrift toont het potentieel dat effectief gebruik van productkwaliteitsinformatie in logistieke planning in voedselketens biedt. Ik hoop dat andere onderzoekers kunnen voortbouwen op de in dit proefschrift gepresenteerde studies, en dat zij verdergaan met het ontwikkelen en verbeteren van innovatieve logistieke strategiën in voedselketens.

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About the author

Willem Antoon Rijpkema was born in Boxmeer, the Netherlands, on December 1st 1982. He attended the athenaeum at Elzendaal College, where he obtained his diploma in 2001. In 2002, Willem started a BSc course in agrotechnology, which he completed in 2006. As he was interested in both engineering and management science, he enrolled in two MSc programmes. In 2008 he obtained an MSc degree in agricultural and bioresource engineering after completing an MSc thesis at the Systems and Control Engineering group headed by Prof. Dr Ir Gerrit van Straten and performing an internship at Stork Food Systems. Willem obtained an MSc in management and economics in 2009, after writing a thesis at the Operations Research and Logistics group headed by Prof Dr Ir Jack G.A.J. van der Vorst. This MSc research was performed in close collaboration with VION Food Group.

After finalising his MSc studies Willem started as a PhD candidate at the Logistics, Decision and Information Sciences group (LDI) of Wageningen University. He was supervised by Dr Roberto Rossi (co-promotor), Dr Eligius M.T. Hendrix (co-promotor), and Prof Dr Ir Jack G.A.J. van der Vorst (promotor). Willems research topic was the development of methods for effective use of product quality information in food supply chain logistics. During the first years of his PhD research, Willem built on experience he had previously gained in the meat supply chain by participating in the EU-funded *Q-porkchains* project. In the last two years of his studies, Willem gained experience in fruit and vegetable supply chains by participating in the EU-funded *Veg-i-Trade* project. In both projects, Willem collaborated with numerous partners from both research and industry and disseminated his research at various international conferences and consortium meetings. Between October 2012 and December 2013, Willem was employed as a lecturer at the Operations Research and Logistics group of Wageningen University. During this period, he was involved in a variety of courses, including Food Logistics Management, Advanced Supply Chain Management, and Sustainable Supply Chain Management. After final-

Based on the stained glass family arms in the church of Akkrum (Fr), 1760 A.D.

ising his PhD thesis, Willem started a job as a supply chain coordinator at FrieslandCampina, where he continues to work on challenges in food supply chain logistics.

In addition to his studies, Willem has been involved in a number of extracurricular activities. He was an active member of study association *Heeren XVII*, organizing various events, and functioning as the treasurer for a year. Furthermore he was a member and chair of the PhD-council of the WASS research graduate school. In this function, he organized a variety of activities, chaired meetings, and was a representative for the PhD-students. Apart from this, Willem has a broad range of interests, and enjoys traveling, meeting people, food, and sports (cycling, hiking, skiing).

Willem A. Rijpkema
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Wageningen School of Social Sciences

Name of the course	Department / Institute	Year	ECTS (=28 hrs)
I. General part			
Techniques for Writing and Presenting a Scientific Paper	WGS	2009	1.2
Scientific writing	WGS	2010	1.8
Project and time management	WGS	2011	1.5
II. Mansholt-specific part			
Mansholt Introduction course	MG3S	2009	1.5
Poster presentation Mansholt peer review	MG3S	2009	1.0
'Quality controlled logistics in pork supply chains'	WASS PhD-day	2010	1.0
'Use of livestock quality estimates for improved product allocation planning to meat processing locations	WICANEM conference, Wageningen	2010	1.0
Participation ELA doctorate workshop	Saint Nazaire	2010	1.0
'Using postponement strategies to reduce planning uncertainty in meat supply chains'	LRN conference, Leeds	2010	1.0
'Effective use of product quality information in meat processing'	APMS conference, Norway	2011	1.0
Dinalog PhD winterschool		2012	1.5
III. Discipline-specific part			
Strategy and Models (MCB-31806)	WUR	2009	6.0
Advanced econometrics (AEP-60306)	WUR	2009	6.0
Writing research proposal	MG3S	2009-2010	6.0
Club methodology LDI section	WUR	2010	1.0
Food Supply Chain Management	WASS	2011	2.5
IV. Teaching and supervising activities			
Supervision MSc students	WUR		2.0
PhD-council, 2 years, 1 ECTS/year	WASS	2009 - 2011	2.0
Organisation career day	WASS	2010 - 2011	0.5
TOTAL			39.5

Notes