Logistics network design & control: managing product quality in a blooming sector

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Thesis

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Preface and acknowledgements

The PhD program, and particularly the defence, is often compared to personal happenings like marriage or birth. Although I don't have experience with the latter, I think it is safe to say that the PhD program, from the first research steps up to the defence, is beyond compare. It is a once-in-a-lifetime experience. Although every now and then it felt more like a struggle, it has been a privilege to get the opportunity to pursue a PhD. Above all, it has led to this great feeling of finishing the program and proudly presenting my PhD thesis. I wouldn't have come to this point without the help of others and I would like to thank them here.

The first people I would like to thank are my supervisors who helped me throughout the years. I could always turn to them when I was struggling with my research, but also when I was struggling with more personal issues. And they didn't forget about the gratifying successes. The first article published, a nice presentation at a conference, finalizing this thesis, they didn't let it just pass by.

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I am going to switch to Dutch now, because I would like to thank my family and friends in a language that is more familiar to me. Ik wil liever geen namen noemen omdat ik geen mensen wil vergeten, maar ik maak een uitzondering voor Karin en Madelinde. De eerste volleybalteam-ervaring deed iets heel anders vermoeden, maar dank jullie wel voor jullie warme vriendschap. Ik wil verder iedereen bedanken die me de afgelopen vier jaar heeft bijgestaan. Zonder familie en vrienden had ik dit niet volgehouden.

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CODP	Customer order decoupling point
DaVinc^{3}i	Dutch Agricultural Virtualised International Network with Coordination, Consolidation, Collaboration and Information availability
FlSCM	Floricultural supply chain management
FP	Form postponement
FSCN	Fresh produce supply chain network
GWP	Global warming potential
HOS	Hybrid optimisation and simulation
KPI	Key performance indicator
LOS	Logistics orchestration scenario
LSP	Logistics service provider
MILP	Mixed integer linear programming
QCL	Quality controlled logistics
SCM	Supply chain management
SCN	Supply chain network

Chapter 1

General introduction

1.1 The floricultural sector

Tulips, 'Keukenhof', wide flower fields, the biggest flower auction in the world, when one thinks of floriculture, one thinks of the Netherlands. The Dutch floricultural sector is a vivid sector with a long tradition. Breeders, growers, Logistics Service Providers (LSPs), traders, florists, they all work together to make sure that we have a nice bouquet on our kitchen table and cheerful plants in our gardens. They also make sure that we have a large assortment to choose from, from the well-known rose to the remarkable zanthedescia and from the traditional geranium to the exotic orchid. Together with the profound knowledge on growth and care of floricultural products and an adequate logistics infrastructure to collect and distribute floricultural products, the complete assortment that is offered has made the Dutch floricultural sector to what it is today: the trading hub for Europe.

The establishment of floricultural clusters was crucial to becoming an important trading hub. In the old days, fertile areas evolved into grower regions. The growers sold their products to traders who then sold the products at street markets. Being a living product, little time was to pass between harvest and sale and therefore the growers, traders and street markets were located close together. To counterbalance the gradual increase in power of the traders, the growers joint forces and established auctions in each grower region to sell their products. This completed the floricultural clusters. Over time, the assortment has grown and products are also supplied from abroad, like South America and Africa. The flowers and plants are not only sold in the Netherlands anymore, but far beyond, up to Russia. The network has changed considerably and will keep changing due to new developments. This means that one has to think about the consequences of the developments, on the short term, but especially on the long term. This has been the driver for the project DaVinc^{3}i (Dutch Agricultural Virtualized International Network with Coordination, Consolidation, Collaboration and Information availability).

DaVinc^{3}i, co-financed by Dinalog and the Horticultural Commodities Board, was started by a consortium of industry professionals and academics in 2011. Over 4 years, DaVinc^{3}i has evolved into a platform to discuss the challenges that the floricultural sector is facing, related to virtualisation and collaboration. This was done in bimonthly meetings with a core team, consisting of industry professionals from the Dutch auction FloraHolland and 'The Association of Wholesale Trade in Horticultural Products (VGB)' and academics from Wageningen University, Eindhoven University of Technology and VU University Amsterdam; and twice-yearly meetings with the core team and partners from across the floricultural sector, e.g. growers, traders and LSPs. Over 60 master and bachelor students, two PhD students and two postdocs have looked into different strategic issues within three work packages dedicated to logistics, ICT and business models respectively. This PhD thesis and the corresponding research were part of the work package on logistics. In addition to the project meetings, interviews were held with respondents from across the floricultural sector. This has contributed to the author's knowledge on floricultural products and floricultural logistics and supported the study of insights in real-life cases.

There are several challenges in floricultural logistics due to technology and market developments. For example, cut flowers are more and more transported from South-America to the Netherlands in reefers (i.e. refrigerated containers). Due to the controlled conditions within reefers, a high product quality can be preserved for several weeks. If these controlled transport conditions are translated to controlled storage conditions, this may provide opportunities to keep stock down the supply chain. Strategically locating stock can decrease the delivery time to customers. This anticipates the requirements from supermarkets and web shops, which are gradually winning market share at the expense of florists. The different market segments are served by closed logistics sub-networks, but there may be potential for one logistics network with differentiated logistical services. The emergence of web shops furthermore makes that trade becomes virtual and products do not have to be physically present at the point of sale. This affects the supply chain and accompanying logistics network. Altogether, the floricultural sector needs to coordinate a large number of chain activities, control both global and local flows, meet differentiated market requirements and balance different objectives.

1.2 Floricultural supply chain management

Supply Chain Management (SCM) encompasses the planning and control of all information and logistics flows from sourcing to sales[1]. *Floricultural Supply Chain Management (FlSCM)* then encompasses the SCM of cut flowers and potted plants. Similar to food SCM and additional to general SCM, one of the complicating factors in FlSCM is the perishability of the products. Perishable products are products that decay throughout the supply chain due to environmental conditions (temperature, humidity, etc.). More specifically, perishable products are products for which quality can be preserved at an acceptable level for at most 30 days (Van Donselaar et al., 2006). This applies to some potted plants and most cut flowers. When quality can only be preserved at an acceptable level for just a few days, the products are classified as days fresh products (Van Donselaar et al., 2006) or fresh produce (Blackburn & Scudder, 2009). This applies to most cut flowers. Although both potted plants and cut flowers react to environmental conditions, there is a distinction. Potted plants can decay, but

[1] Derived from the definition of supply chain management by the Council of Supply Chain Management Professionals; https://cscmp.org/about-us/supply-chain-management-definitions

up to a certain point the decay can be reversed (e.g. a plant can be rehydrated when the humidity in the supply chain has been too low). The decay of cut flowers, on the other hand, is irreversible. Product quality deteriorates from the moment a flower is picked. Based on floricultural product characteristics and the appointed product type classification, Figure 1.1 depicts a classification of SCM and a positioning of FlSCM. It shows that FlSCM covers the spectrum from almost non-perishable up to highly perishable product supply chains.

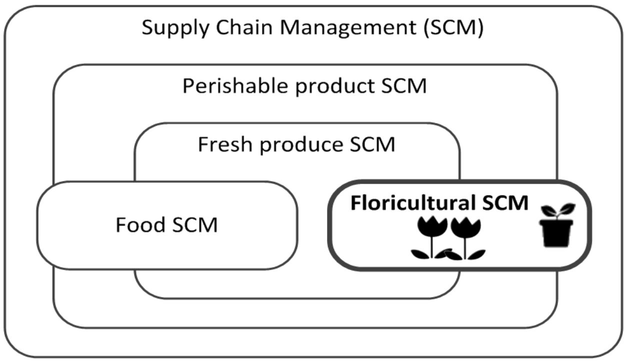


Figure 1.1: Classification of supply chain management

To provide an outline, the key FlSCM concepts that are used throughout this thesis are listed next.

Product quality decay

As perishability of products entails that product quality changes with time, *product quality* and *product quality decay* are important aspects in FlSCM. Specific characteristics are:

- For potted plants, product quality shows in the appearance of the plant (e.g. number of leafs per stem and greenness of leafs). For cut flowers it is mainly defined as *vase life*, i.e. the time flowers can be put on a vase at room temperature (Tromp et al., 2012).
- Product quality is *dynamic* as it changes with time, where the initial product quality is established at the time of harvesting (cf. Fredriksson & Liljestrand, 2014).
- Product quality is *heterogeneous* due to e.g. seasonality and differing environmental conditions during logistics activities. Part of the heterogeneity is predictable, which is denoted as *variability* in product quality. Inherent to the growth and processing of living materials, part of the heterogeneity is unpredictable, which is denoted as *uncertainty* in product quality (cf. Verdouw et al., 2010).

Quality Controlled Logistics (QCL)

By using tracking & tracing systems, e.g. based on RFID, real-time information can be provided on the location of products in the network and the durations of logistics activities. By using temperature monitoring systems, e.g. using time temperature indicators and data loggers, real-time information can be provided on environmental conditions during transport, storage or processing. These technologies contribute to the ability to predict product quality at any point in the supply chain, which in turn renders potential for innovative logistical concepts that use information on product quality, i.e. *Quality Controlled Logistics or QCL* (Van der Vorst et al., 2011). The product quality information can be exploited real-time at an operational level, e.g. redirecting product flows when the predicted product quality cannot fulfill the requirements of the original destination anymore. The product quality information can also be exploited at a strategic level, e.g. restructuring the logistics network in order to eliminate bottlenecks with respect to decay.

Network design and network control

Based on different decision levels, QCL problems can be divided in network design and network control problems:

- *Network design* is concerned with setting the structure of a logistics network at a strategic level, i.e. determining the function and location of logistics hubs and allocating capacities and flows (Chopra & Meindl, 2013).
- Given the network design, *network control* is concerned with managing logistics operations at a tactical and operational level, which includes demand forecasting, inventory management, materials handling, order management, packaging, procurement, transportation management and warehousing management (Murphy & Wood, 2011).
- *Network configuration* denotes a network design that includes network control features.

Detail, retail and e-tail markets

The logistics network is designed and controlled to serve different types of markets.

- *Detail markets*, like florists and street markets, are specialized sales channels focused on floricultural products.
- *Retail markets*, like supermarkets and home improvement centres, are unspecialized sales channels where floricultural products are a side-product.
- *E-tail markets*, although still in its infancy in the floricultural sector, are specialized or unspecialized web-based sales channels.

Supply and demand driven chains

Different types of markets need different types of supply chains with different *Customer Order Decoupling Points (CODPs)*, i.e. the strategic stock point from where customers are delivered (Olhager, 2010). For example, the traditional supply chain that distributes products to florists is a supply chain with the CODP at the point of sales. Stock is held at the florists where processes like bouquet making and packaging are executed. This type of supply chain is denoted as *supply driven* or *push chain*. When the CODP is at the grower, products can be customized according to the wishes of the customer at any point in the chain. This type of supply chain is denoted as *demand driven* or *pull chain*.

Different types of supply chains serve different purposes. A supply driven chain is focused on *efficiency*, where a demand driven chain is focused on *responsiveness*, i.e. being able to deliver and adjust according to customer requirements. This means that time and flexibility become important, but also being able to deliver the right *product quality*.

Logistics network problems
Different types of supply chains induce different types of logistics network problems:

- When the CODP is at the customer, the main function of the supply chain is to distribute unprocessed products. The logistics network problem then comes down to a *hub location problem*, which deals with the location of hubs and allocation of flows from suppliers to hubs, between hubs and from hubs to customers (Alumur & Kara, 2008).
- When the CODP is at the grower, the main function of the supply chain is to distribute and process products. The logistics network problem then comes down to an *integrated hub location and process allocation problem*, in which, in addition to the hub location problem, it is decided at which hubs to process.
- When the CODP is at a hub, the main function of the supply chain is to distribute, process and store products. The logistics network problem then comes down to an *integrated hub location and process and stock allocation problem*, in which, in addition to the integrated hub location and process allocation problem, it is decided at which hubs to keep stock.

1.3 Research design

The floricultural sector needs to handle different products with different levels of perishability, coming from different grower regions and going to different customer regions, in order to meet differentiated market requirements. This fits the challenges in perishable product SCM and food SCM to deal with multiple products with different product quality decay and supply and demand patterns (Akkerman et al., 2010a). As grower and customer areas are shifting, the floricultural clusters in the Netherlands are not necessarily the preferred logistics hub locations. The shift asks for redesign of the logistics network towards a European logistics hub network. As retail and e-tail markets are gaining market share at the expense of detail markets, the floricultural supply chain network shifts from being supply driven to becoming more demand driven. This asks for an examination of CODP allocations. Network designs should furthermore be evaluated at the network control level to gain insight in the actual performance, sensitivities and robustness of logistics networks for the future floricultural sector.

The complexity in (the combination of) the decisions and contexts calls for quantitative models that can assist in the decision-making. Different types of models are thereby suitable for different types of problems and problem characteristics, e.g. optimisation models can be used to design an optimal logistics network (Melo et al., 2009) and simulation models can be used to capture dynamic and stochastic factors (Van der Zee & Van der Vorst, 2005). This research aims to develop different types of quantitative models for FlSCM and reduces the gap of research with a quantitative modelling perspective in the field of perishable product SCM (Akkerman et al., 2010a).

> ***Overall research objective:*** *To develop quantitative modelling approaches that support the (re)design of a perishable product logistics network for supply and demand driven supply chains.*

In this general introduction, a short overview is given of the main challenges the floricultural sector is facing and the research topics that emerge from the challenges. To get a comprehensive overview, the first research aim is to analyse the sector characteristics and developments in more depth and to derive associated research gaps in literature. A sector analysis and literature review are conducted to answer the first research question:

> ***RQ1:*** *What are research challenges in modelling logistics networks for perishable products induced by developments in the floricultural sector?*

Results are presented in Chapter 2 and show that FlSCM research challenges can be found in:

- *Incorporation of product perishability in network design problems*
  Perishability of cut flowers and potted plants leads to product quality decay due to logistics operations and consequently to a need to incorporate product perishability in logistics decisions. Current research mainly incorporates perishability at the network control level, and the challenge is to incorporate perishability at the network design level.
- *Expansion of the efficiency-responsiveness trade-off with product quality*
  The logistics system needs to be flexible and responsive, costs and efficiency are still the main drivers and being able to deliver good product quality is one of the success factors for the floricultural sector. A multi-objective approach to decision problems is therefore an important research direction.
- *Integration of network design and network control problems*
  To better deal with demand uncertainty, market differentiation and responsiveness,

integration of decision problems at different decision levels is needed. As the floricultural sector is characterized by the three aspects, integrated network design and control problems are a promising research direction.

- *Integration of optimisation and simulation models*
  Optimisation is mostly used for network design and simulation is mostly used for network control. Just as the integration of decision problems is a research challenge, so is the integration of the applied modelling techniques.

The first three research challenges relate to the type of logistics network problem and the way product quality is addressed. This is denoted as the system. The fourth research challenge relates to the modelling approach. The *system* and *modelling approach* dimensions are the foundation for the research framework of this thesis (Figure 1.2).

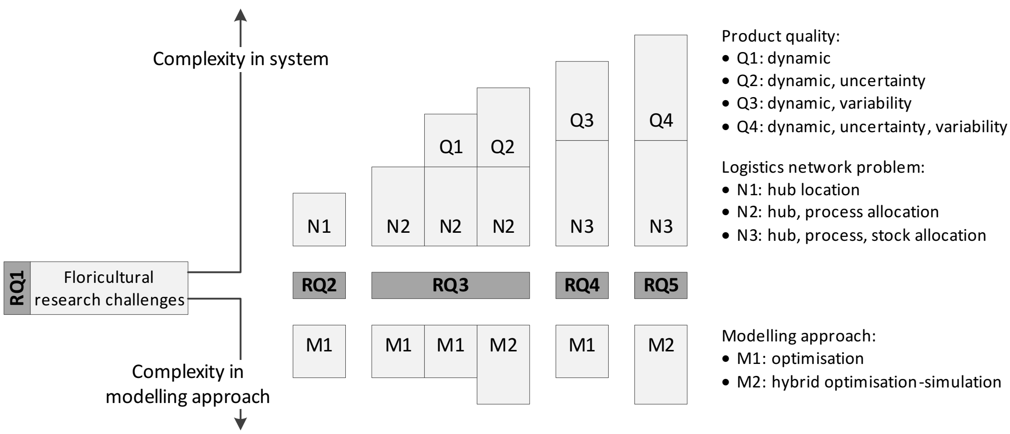


Figure 1.2: Research framework for this thesis

The research framework is developed to structure and expose the complexities within the system and modelling approach dimensions. Different levels of complexity are defined for the different dimensions (see also the definitions in Section 1.2). The first system dimension, the logistics network problem, starts from the basic hub location problem (N1). The complexity of the problem increases in the integrated hub location and process allocation problem (N2) and subsequently in the integrated hub location and process and stock allocation problem (N3). Complexity in the second system dimension, product quality, arises because product quality is dynamic (Q1). The complexity gradually increases when uncertainty (Q2), variability (Q3) and uncertainty as well as variability (Q4) in product quality are addressed. For the complexity in the modelling approach, optimisation (M1) and hybrid (i.e. integrated) optimisation-simulation (M2) are distinguished. The levels of complexity in the framework dimensions are used to define the remaining research questions in this thesis. Next, each research question is presented and subsequently explained.

> ***RQ2****: What are optimal and robust logistics network designs for the European potted plant supply chain network?*

The basic logistics network problem addressed in this thesis is a hub location problem. The Dutch currently have a leading position in the European potted plant supply chain network (SCN). However, due to several developments, this position is under pressure. The use of a logistics hub network and consolidation may help to prevent losing the lead. A case study in the European potted plant SCN is set up to design and analyse hub networks for different future scenarios. As potted plants have a long lifetime, product quality is not taken into account. Optimal logistics hub networks are determined using an optimisation model, more specifically a Mixed Integer Linear Programming (MILP) model.

Hub network design is an important topic in FlSCM and one of the challenges is to take into account the perishability of products. This results in the following research question:

> ***RQ3****: What is the added value of increasing the complexity in modelling product quality and in the modelling approach used for a network design problem?*

One of the main developments within the floricultural sector is virtualisation (i.e. the use of digital representations of products or processes). Virtualisation induces virtual synchronisation of the supply chain into one logical enterprise (Anderson & Lee, 2000). Part of synchronisation is related to integration of virtual and physical processes, e.g. integration of logistics processes, which induces a reconsideration of process locations (Anderson & Lee, 2000). Therefore, the next logistics network problem addressed in this thesis is a hub location problem integrated with process allocation decisions. It concerns an illustrative case in the cut flower SCN. In response to the FlSCM research challenge of incorporating perishability at a network design level, different complexities in modelling product quality decay are applied. In response to the FlSCM research challenge of integrating optimisation and simulation models, different modelling approaches are applied. First, an MILP model is formulated for the logistics network problem without taking into account product quality decay. Second, an MILP model is formulated for the logistics network problem taking into account product quality decay at an aggregate level. Third, a hybrid optimisation-simulation approach is developed for the logistics network problem in which simulation is used to determine product quality in more detail and to include uncertainty in product quality.

With each aspect of product quality that is incorporated in network design, the complexity of the corresponding model increases. Therefore, only essential aspects should be modelled. This results in the following research question:

> ***RQ4***: *What are key factors in modelling product quality decay for a network configuration problem?*

Different markets in the floricultural sector have different CODPs. The position of the CODP is related to the position of processes and stocks (Olhager, 2010). The next logistics network problem addressed in this thesis is therefore a hub location problem integrated with process and stock allocation decisions. In response to the FlSCM research challenge of integrating decision problems, it integrates tactical stock decisions with strategic network design decisions. It concerns an illustrative case for the cut flower SCN. To gain further insight in the impact of different aspects of product quality on network configuration, an MILP model is formulated that takes into account the different aspects, e.g. variability in product quality due to seasonality.

The models show how perishability and product quality decay can be incorporated in network design and network configuration, but they do not show the implications for the floricultural sector. This induces the following research question:

> ***RQ5***: *What are suitable logistics networks for different supply and demand driven cut flower supply chains?*

Bringing everything together, the research in this thesis ends with an integrated hub location, process and stock allocation problem for perishable products with variability and uncertainty in product quality, solved with a hybrid optimisation-simulation approach. It is a case study for the cut flower SCN in which logistics hub networks are designed and analysed for different supply and demand driven supply chains. In response to the FlSCM research challenge of expanding the objectives, a multi-objective approach is used to optimise and evaluate the network configurations with respect to efficiency, responsiveness and product quality.

1.4 Thesis outline

The chapters in this thesis follow the research framework as depicted in Figure 1.2. Chapter 2, entitled "Floricultural supply chain network design and control: industry needs and modelling challenges", shows the research challenges for quantitative modelling in floricultural supply chain networks. Chapter 3, entitled "Logistics orchestration scenarios in a potted plant supply chain network", defines and analyses different logistics orchestration concepts, i.e. hub networks and logistics consolidation, for the European potted plant supply chain network. In Chapter 4, entitled "Hybrid optimisation and simulation to design a logistics network for distributing perishable products", a hybrid simulation and optimisation approach is developed to enable the inclusion of product quality decay and product quality uncertainty in network design. In Chapter 5, entitled "Logistics network configuration for perishable products: modelling -variability in- product quality decay", an optimisation model is developed to be able to incorporate product quality decay as well as product quality variability in network configuration. In Chapter 6, entitled "Effective logistics networks for the distribution of perishable products in supply and demand driven supply chains", different types of cut flower supply chains are optimised and evaluated in order to create a ranking of logistics network configurations for distributing perishable products. The conclusions from the chapters are summarized in Chapter 7, which furthermore contains the integrated findings, managerial implications, discussion and suggestions for further research. Finally, a summary of this thesis (page 185) and an overview of publications (page 201) are provided.

Chapter 2

Floricultural supply chain network design and control: industry needs and modelling challenges

De Keizer, M., Van der Vorst, J.G.A.J., Bloemhof, J.M., & Haijema, R. (2015). Floricultural supply chain network design and control: industry needs and modelling challenges. *Journal on Chain and Network Science, 15(1)*, 61–81. doi:10.3920/JCNS2014.0001

Abstract

The floricultural sector is confronted with market developments that force a redesign of the European logistics network. Via workshops and interviews with key stakeholders the main developments and industry needs are identified. These are then summarized in three central themes that require further investigation, i.e. decision problems (e.g. network design and control), context factors (e.g. demand uncertainty and product perishability), and objectives (e.g. efficiency and product quality). Next, 17 articles that review Supply Chain Management (SCM) research are analysed to get more insight in the state of the art on these themes and to identify the main issues within the themes and their interrelationships. This resulted in a conceptual research framework in which particular attention is given to how decision problems could be modelled and solved in order to get quantitative insights in the impact of logistics network redesign. Successively, 71 SCM articles were analysed in depth to classify current SCM research and to determine research gaps and challenges. Results show that Floricultural SCM research challenges can be found in integrated, quality-driven and responsive network design and control using hybrid optimisation and simulation.

2.1 Introduction

The floricultural sector is of world-class quality, and the Netherlands serves as the main trading hub for Europe (Porter et al., 2011). Due to the strong cluster of commerce and logistics in the floricultural sector, most products from (inter)national growers that are destined for Europe flow through the market places in the Netherlands. However, several market developments are fundamentally changing the basic principles for the European logistics system. The production of flowers and plants is shifting (e.g. more production coming from Africa and South America), customers are situated further away (e.g. expanding Eastern European market) and business processes and sales channels are becoming virtual (e.g. business-to-business and business-to-consumer web shops, virtual auction clock). The development of a global supply chain network and more importantly the emergent virtualisation of the supply chain network (Verdouw et al., 2012) lead to more direct flows bypassing the current Dutch physical logistics network. It creates necessities and opportunities for redesigning the European logistics network and its coordination and control. Renewed optimisation of the logistics network and analysis of the performance of redesigns in a quantitative way can thereby support stakeholders in their decision-making.

Research on floriculture is mostly conducted on biological and technological aspects like quality change modelling (Tromp et al., 2012; In et al., 2009). Apart from the auctions (Van Heck, 2001), floricultural Supply Chain Management (SCM), which concerns the management of flows of potted plants and cut flowers, is not discussed much (Shukla & Jharkharia, 2013a). Potted plants and cut flowers can be defined as perishable products, i.e. product quality or value declines over time depending on environmental factors like temperature and humidity. Hence, floricultural SCM is part of perishable SCM (Blackburn & Scudder, 2009) and is closely related to food SCM (Bourlakis & Weightman, 2003). These disciplines study the consequences of perishable product and food characteristics on the management of supply chains. They have received increasing attention due to food quality and food safety issues (Akkerman et al., 2010a). Although there are some reviews on perishable SCM and food SCM (e.g. Ahumada & Villalobos, 2011a; Akkerman et al., 2010a; Amorim et al., 2011; Rajurkar & Jain, 2011; Shukla & Jharkharia, 2013a), to the best of the authors' knowledge, there is no comprehensive literature review on floricultural SCM and modelling.

The aim of this research is: (1) to define current developments in the floricultural sector and derive main themes that require further investigation for the industry to be able to cope with these developments; (2) to identify the state-of-the-art of research on these themes; and (3) to identify research gaps and challenges for future research.

The remainder of this chapter is organised as follows. First, the research is explained in Section 2.2. Then, a description is given of the floricultural sector, its logistics, developments and industrial needs in Section 2.3. Next, the development of a floricultural SCM conceptual research framework is described in Section 2.4. After that, in Section 2.5, a research classification is given from which research challenges are derived. The chapter ends with a conclusion in Section 2.6.

2.2 Research design

This research aims to analyse research on SCM and modelling from the perspective of the floricultural sector. As literature on floricultural SCM is very limited, an explorative study is conducted, consisting of the following three steps (Table 2.1).

Step 1. Sector analysis
To get an initial overview of developments in the floricultural sector, desk research is conducted on documents that describe developments in the sector. This first overview is refined in three rounds of semi-structured interviews and workshops with sector experts in the Netherlands. The first round is used to complement the overview of developments. The second round is used to broaden the view on the developments. The third round is used to verify the overview of developments and translate the developments into industrial needs. In each round the overview obtained up to that point is used as guidance in an open discussion. The participants in the various rounds are: (1) people engaged in logistics at each link in the floricultural supply chain, i.e. growers (6 Small and Medium-size Enterprises (SMEs)), two employees of Dutch auction company FloraHolland, traders (5 SMEs) and logistics service providers (2 SMEs); (2) people from round 1 and other growers (2 SMEs), traders (2 SMEs) and logistic service providers (2 SMEs), as well as 3 logisticians from sector organisations that oversee the complete supply chain ('The Association of Wholesale Trade in Horticultural Products' (VGB) and 'Product Board for Horticulture'); (3) three representative sector experts, i.e. assistant director of a logistics service provider, head of the VGB project department and manager supply chain development of FloraHolland. From identified characteristics, developments and needs the most prevalent SCM issues are deducted and summarised in three central themes, i.e. decision problems, context factors and objectives, which require further investigation.

Step 2. Framework development
To develop a conceptual research framework, an analysis is conducted of recent review articles that discuss the SCM issues formulated in step 1. To demarcate the analysis, using the known literature gap with regard to SCM and modelling (Akkerman et al., 2010a), a focus on review articles with a quantitative modelling perspective is chosen. A search for SCM research in Scopus and Web of Science, using terms ['review' or 'overview'], and ['supply chain management'], and ['quantitative' or 'operations research' or 'mathematical' or 'analytical' or 'optimisation'], results in a collection of 724 articles.

To create a broad view, floricultural-related keywords like ‘fresh produce’ or ‘perishable’ are not used. Articles older than two years with fewer than 20 citations are discarded, resulting in a collection of 117 articles. To avoid going into detail, only review articles are selected in this step. Based on a title and abstract analysis, review articles that address the formulated SCM issues are selected. This results in a final collection of 17 review articles, of which ten are general SCM reviews, five are food SCM reviews and two specifically address virtualising supply chains. An analysis of these 17 articles leads to an overview of SCM concepts and relations which is then used to construct a conceptual research framework for floricultural SCM.

Step 3. Research gap analysis
The collection of review articles in step 2 creates a summary of prior research. A forward citation search for the reviews is performed to obtain a representative outline of current supply chain (SC) modelling research (Webster & Watson, 2003). This resulted in a collection of 353 articles. The framework from step 2 is then used to classify current SC modelling research. Based on a title and abstract analysis, articles that use a quantitative modelling approach are selected and subsequently articles that address a decision problem with context factors that can be found in the conceptual research framework are selected. This results in a collection of 71 articles published from 2005 onwards. A classification and analysis of these articles is then conducted to identify important research topics and gaps. Research challenges are defined and discussed in view of the sector developments and needs identified in step 1.

Table 2.1: Research design

Step	Method/material	Output
1. Sector analysis	Desk research Interviews Workshops	Sector characteristics Sector developments Industrial needs Key supply chain management themes
2. Framework development	Review of literature on key supply chain management themes	Conceptual research framework
3. Research gap analysis	Analysis of literature on supply chain modelling	Research challenges

2.3 Sector analysis

Based on desk research and interviews and workshops with experts, the current system and developments in the floricultural sector are described. Furthermore, key characteristics of floricultural supply chains and the issues that need to be studied from an industrial perspective are presented.

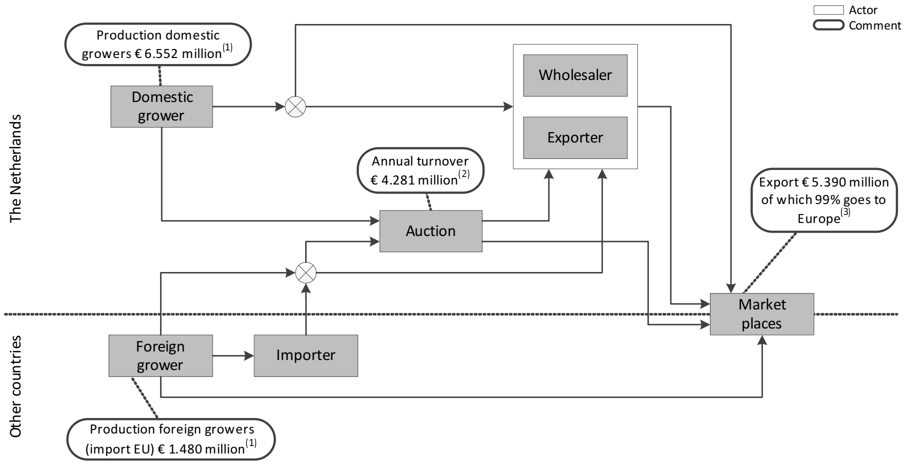
2.3.1 Sector characteristics

As Porter et al. (2011) mention, the Netherlands is the heart of the international floricultural sector and is involved in each step in the process of growing and distributing floricultural products, from breeders to sales outlets. The supply chain network consists of growers, auctions, traders, logistics service providers and market places (Figure 2.1):

- FloraHolland, the biggest flower auction company in the world, has six auction centres for trading in cut flowers (about 70% of turnover) and potted plants (about 30%), a national intermediary organisation and an internationally active import department. FloraHolland is a primary cooperative: the business is owned by roughly 5,000 members, most of them growers in the Netherlands, but also beyond.
- There are three groups of traders: wholesalers, exporters and importers. About 1,200 Dutch traders deal with many (inter)national customers and have a market share of approximately 70% in EU export.
- Transport between chain stages is commonly outsourced to one of over 70 logistics service providers. In some cases the providers execute extra activities like quality control, handling and packaging. On average there are 20,000 truck movements per day, of which about 1,800 are between the Dutch auction centres.
- Sales channels in the (inter)national market places can be divided into retail, i.e. unspecialised shops where floricultural products are a by-product (supermarkets, service stations, gardens and home improvement centres, etc.); detail, i.e. specialised shops focused on floricultural products (independent garden centres, flower shops, street markets, etc.); and e-tail, i.e. web-based shops.

Different products and markets have different characteristics and requirements that can influence the supply chain network. Some illustrative product characteristics are given in Table 2.2. The sourcing areas, for example, are much more global for cut flowers than for potted plants. The product types also have different levels of perishability, which determine the transport mode and storage conditions. Some examples for market characteristics are given in Table 2.3. There are a large number of specialised flower shops that carry a large variety of products as opposed to the small number of home improvement centres that offer a limited variety. Supermarkets order large amounts of only a few products well in advance, while street markets want to order small amounts of products immediately for selling on the same day.

A characteristic aspect of the floricultural sector is high supply uncertainty related to product quantity as well as to product quality, origin and timing. It arises from the difficulty in predicting product quality, due to the influence of time and environmental conditions, seasonality, etc. On the demand side the same type of uncertainties apply as a result of diverse customer orders, increasing customer requirements (i.e. guaranteed vase life, fast delivery), weather-dependent sales, global competition, etc. (Verdouw et al., 2010).



Sources:
(1) http://ec.europa.eu/agriculture/fruit-and-vegetables/product-reports/flowers/statistics-2013_en.pdf
(2) http://www.floraholland.com/media/1525240/KengetallenEN2012.pdf
(3) http://www.hbagbloemen.nl/upload/Kengetallen2013.pdf

Figure 2.1: Dutch floricultural supply chain network

Examining the above description, (dis)similarities can be found between the floricultural supply chain and other perishable product supply chains, such as vegetables and fresh food supply chains. Essential characteristics, like perishability and supply and demand uncertainty, are similar. Differences can be found in the market shares of sales channels, the many flower and plant varieties and the large number of SMEs. Detail shops are the main sales channel in the floricultural sector, whereas retail shops are the main sales channel in the food sector. Together with the large product variety, this means that the auction in the floricultural sector is highly influential, leading to a more supply-driven chain compared to the food sector. Due to the large number of companies, cooperation and collaboration plays a prominent role in the floricultural sector.

The characteristics of the floricultural sector can be summarised as: (1) high demand and supply uncertainty in product quantity as well as product quality, origin and timing; (2) different types and levels of perishability; and (3) product and market differentiation, meaning that different products and markets have different supply chains with different logistics requirements.

2.3.2 Sector developments

In the second part of the sector analysis, developments and industrial needs for the floricultural sector are determined (Figure 2.2). First, global developments are determined at an aggregate level. Then, sector developments, and logistics and information developments are determined at a more detailed level. Finally, the industrial

Table 2.2: Supply chain characteristics of different floricultural product types

	Cut flowers	Potted plants
Perishability	Lose about 15% of value per day; Product quality expressed in vase life: time between production and point at which the product becomes unacceptable under defined environmental conditions (Luning & Marcelis, 2009)	Under optimal conditions almost non-perishable; Product quality expressed in height, number of stems per pot, number of flowers per stem, etc.
Network scope	Global sourcing, European sales	European sourcing, European sales (local-for-local)
Key trade mechanism	Auction	Direct trade
Network type	Supply driven	Demand driven

needs are derived from the developments. In this section the developments are discussed, the industrial needs are discussed in the next section and subsequently the key SCM themes are summarised.

The floricultural sector is organised as a dynamic supply chain network in which the roles of supply chain actors are changing. On the one hand, due to *specialisation*, processes and links in the chain become more fragmented and supply chain stages become more dependent on each other to supply the complete assortment to the market. On the other hand, due to scaling of growers and traders, the auction company as a central institution that brings together supply and demand becomes less important. Growers and traders are competing for value-added services, which is also apparent in the forward integration of growers and backward integration of traders. Logistics service providers in particular will develop to offer a full service with increased flexibility and responsiveness. This enables them to cope with differentiated demand for logistical services from different market segments.

Also due to *specialisation* and *scaling*, the product assortment shrinks and a clear split in commodities and specialties emerges. Commodities, which have a relatively low price, low supply and demand uncertainty and long lead times compared to specialties, are leading in the configuration of the logistics network due to its large volumes.

Table 2.3: Supply chain characteristics of different floricultural market types

	Detail	E-tail	Retail
Number of sales points	Large	Very large	Small
Product variety	Large	Large to medium	Limited
Type of product	Specialized	Customized	Mass-customized
Order size	Small	Very small	Large
Order lead time	Day	Day	Week(s)
Quality	High	As specified	Guaranteed

Figure 2.2: Developments and industrial needs in the floricultural sector

Stimulated by *containerisation* together with improved *conditioning technologies* and new transport modalities, the use of refrigerated containers (reefers) within the floricultural supply chain is gradually increasing. These containers make it possible to control the environment during transport and handling, and even to hold inventory. It increases the possibilities to preserve high product quality over longer periods of time. In particular, import flows and rail and sea transport (Van der Vorst et al., 2012) are starting to deploy these reefers, which creates an increase in feasible transport distance and/or time. This in turn changes the sourcing areas as well as the throughput centres in the floricultural sector. Whereas Western Europe used to be the main source for European demand, the production of cut flowers is (partly) shifting to equatorial regions due to better weather conditions, and the production of plants is rising in Eastern Europe due to low costs.

Visibility throughout the floricultural supply chain has increased due to *digitisation* and automation. RFID tags are attached to loading units, and tracking & tracing (T&T) systems at actor level are initiated. The T&T system at actor level should subsequently evolve to a chain-wide T&T system. In addition, time temperature indicators or other condition monitoring systems can be attached to loading units, e.g. to reefers. This all contributes to the ability to store and communicate real-time information along the supply chain and the ability to predict product quality at any point in the supply chain.

Information systems enable *information sharing* which is mostly driven by commercial interests in the floricultural sector. This leads to dedicated logistics sub-networks within the total supply chain network for different commercial chains. Information systems also enable the emergence of virtualisation within the traditional floricultural supply chain network. Supply chain actors reach their customers via information systems instead of or alongside physical systems (Verdouw et al., 2012). The use of business-to-business market information systems in the flowers and plants industry has expanded enormously in the last few years. The most important developments are the digitisation of the auctioning process and the emergence of on-line trade platforms. Also a number of business-to-consumer (B2C) web shops have emerged in the floricultural sector, mainly for flowers. Communication with consumers via smartphone apps is in its infancy. Overall, B2C internet trade is still minor in comparison with traditional market channels like flower shops and supermarkets, because most consumers still want to see flowers and plants before buying.

Due to *virtualisation*, *globalisation* and improving *conditioning technologies*, the market reach is increasing. Eastern European countries, where wealth and consequently demand for luxury products like cut flowers is growing, are becoming a more significant market segment. Due to *urbanisation* and *individualisation*, buying patterns are changing. Consumers are increasingly buying an experience rather than a product, and they are looking for convenience and added value. As a result, consumers are shifting from specialised flower shops (detail) to one-stop-shopping in supermarkets (retail) and one-click-away web shops (e-tail). This shift on the one hand increases the infrequent large volume flows, and on the other hand the frequent small volume flows.

At the moment, the floricultural sector is driven mainly by efficiency. This means that it is focused on adding value while decreasing logistics costs. For example, a large sector project was initiated in 2011 to decrease transportation costs between the different market places by reorganising logistics collaboration (Van Veen & Van der Vorst, 2011). Due to *scaling* of growers, logistics service providers and traders, efficiency-driven developments are even more important. Part of adding value is delivering the right quality at the right time (i.e. being on time is more important than speed). Although there are some initiatives to improve *sustainability*, e.g. a project called GreenRail started in 2008 to shift transport from road to rail, sustainability is not explicitly valued in floriculture. The sector does expect, however, that customers will increasingly ask for it.

2.3.3 Industrial needs

The above-mentioned developments increase the complexity of the supply chain network. They lead to industrial needs to cope with this complexity, which are described next (Figure 2.2).

The supply chain network should be able to coordinate a large variety of chain links, nodes and processes, to control both global and local flows, to meet differentiated market requirements, to trade off different objectives, etc. The current logistics network might no longer be appropriate as it was configured on the basis of rather straightforward chains with a clear objective and limited requirements. It should be evaluated with respect to the new logistics requirements and reconfigured where it is not performing well enough. This reconfiguration could concern, for example, decisions on the level of customer-specificity of logistics flows at different nodes, or incrementally bundling assortments at different nodes. Along with a reconfiguration of the logistics network, a reconfiguration of service providers is needed so that they fit the logistics network. They should be flexible and responsive, and they should support market differentiation and service diversification. The situation for the transport network is also changing. As new modalities are introduced, the possibilities are increasing for synchromodal transport, i.e. dynamically switching between transport modalities at any point in the network. These possibilities could also impose new restrictions on the transport network, e.g. only a limited number of harbours are able to serve the largest ships. Within the logistics and transport network a lot of information is or could be made available about product flows, e.g. location, time, product quality, etc. If this information is not only available at discrete time points but in real time, decisions can be made as early as possible and preventive rather than reactive actions can be taken. Overall, because developments affect the whole sector and not just one actor in the sector, vertical as well as horizontal collaboration is needed to be able to cope with those developments. This also counters the disintegration of the supply chain network into closed logistics sub-networks, and can cause a gradual shift from optimising these subnetworks to optimising the total supply chain network.

2.3.4 Key SCM themes

The most prevalent SCM issues are deducted and divided in themes. The industrial needs define the ***decision problems*** the floricultural sector faces, which are divided into strategic *network design* problems (e.g. redesigning transport network, reconfiguring logistics network) and more tactical *network control* problems (e.g. use of realtime information to support logistical decision making). The sector characteristics define the ***context factors*** that put specific requirements on the logistics network: *supply* and *demand uncertainty*, *perishability*, *product* and *market* differentiation. Finally, the logistics developments define the ***objectives***: *efficiency*, *responsiveness* and *product quality*. The themes and issues are used in the next section to analyse SCM literature reviews and define the research framework.

2.4 Framework development

The SCM themes are used to search for literature reviews that discuss one or more of the SCM issues, which resulted in a collection of 17 review articles (Table 2.4). The analysis of the reviews is then focussed on discussions about (aspects of) decision problems, whether and how context factors influence the types of decision problems, how the types of decision problems influence objectives, and how the decision problems can be modelled and solved. This is finally used to develop a conceptual research framework.

Network design - The floricultural sector is shifting from a traditional supply chain to a virtual supply chain, which makes supply chain network reconfiguration or redesign an important issue (Ho et al., 2003). In network (re)design, facility location decisions play a critical role (Melo et al., 2009). Anderson & Lee (2000) show how a traditional supply chain can change into a virtual supply chain. The first step is to integrate processes of the existing supply chain, which induces renewed decisions on process allocations (i.e. where to execute which activity) and inventory allocations (i.e. determining the location of stocking points). To avoid sub-optimality, these decisions should be regarded in an integrated perspective with facility location decisions (Melo et al., 2009). The second step is to improve collaboration and control with suppliers and customers; this ensures that product customisation can be performed in a shorter time period. The last step is to synchronise the supply chain across players into one virtual enterprise; this ensures that mass customisation can be performed in a tailor-made way. The steps can cause a shift in the Customer Order Decoupling Point (CODP), 'the point in the product value chain that divides the material flow that is forecast-driven (upstream the CODP) from the flow that is customer-order-driven (downstream the CODP)' (Olhager, 2010). This CODP shift adds to the complexity of SCM decisions (Klibi et al., 2010).

Table 2.4: Overview of supply chain management reviews

Reference	Title	Focus
Shukla & Jharkharia (2013a)	Agri-fresh produce supply chain management: a state-of-the-art literature review	Food SCM
Amorim et al. (2011)	Managing perishability in production-distribution planning: a discussion and review	Food SCM
Rajurkar & Jain (2011)	Food supply chain management: review, classification and analysis of literature	Food SCM
Zhang et al. (2011)	Petri-net based applications for supply chain management: an overview	General SCM
Akkerman et al. (2010a)	Quality, safety and sustainability in food distribution: a review of quantitative operations management approaches and challenges	Food SCM
Choi & Sethi (2010)	Innovative quick response programs: a review	General SCM
Klibi et al. (2010)	The design of robust value-creating supply chain networks: a critical review	General SCM
Ko et al. (2010)	A review of soft computing applications in supply chain management	General SCM
Ahumada & Villalobos (2011a)	Application of planning models in the agri-food supply chain: a review	Food SCM
Chan & Chan (2009)	A review of coordination studies in the context of supply chain dynamics	General SCM
Melo et al. (2009)	Facility location and supply chain management: a review	General SCM
Peidro et al. (2008)	Quantitative models for supply chain planning under uncertainty: a review	General SCM
Sarimveis et al. (2008)	Dynamic modeling and control of supply chain systems: a review	General SCM
Kouvelis et al. (2006)	Supply chain management research and production and operations management: review, trends, and opportunities	General SCM
Meixell & Gargeya (2005)	Global supply chain design: a literature review and critique	General SCM
Ho et al. (2003)	The process and consequences of supply chain virtualisation	Virtualisation
Anderson & Lee (2000)	The Internet-Enabled Supply Chain: From the "First Click" to the "Last Mile"	Virtualisation

Network control - In the case of fresh produce, models for operational decision problems are very important because of the impact of the limited shelf life on logistics decisions (Ahumada & Villalobos, 2011a) and in turn on post-harvest waste (Shukla & Jharkharia, 2013a). The temperature and duration of logistical processes like transport and storage affect the quality of fresh produce. Continuously tracing the product's quality throughout the network broadens the opportunities to incorporate the freshness of products in network control decisions (Amorim et al., 2011). This, among other things, is reflected in decisions about production planning, distribution planning and inventory management together with product quality decay. Handling multiple products with different shelf lives and supply and demand patterns is a particular challenge (Akkerman et al., 2010a).

Integrated network design and control - Network design and control can be viewed as separate decision problems, but there are also interactions, for example, location-inventory problems. On the one hand, network design can define boundaries for network control (Melo et al., 2009). On the other hand, network control should be anticipated at an aggregate level in network design (Akkerman et al., 2010a). Although integrated design and control leads to much more complex models due to large problem sizes, it is required to achieve full optimality (Melo et al., 2009).

Context factors - Just like food supply chain networks (SCNs), floricultural SCNs have specific characteristics that influence the network design and control, such as high demand and supply uncertainty in product quantity as well as product quality (Ahumada & Villalobos, 2011a). Uncertainties, and especially demand uncertainty, are a major factor that can influence the effectiveness of design and control of supply chains, and considerably affect supply chain performance (Peidro et al., 2008; Sarimveis et al., 2008). Product characteristics, like perishability, limited shelf life and interaction effects between products, and market characteristics, like high customer expectations and low profit margins, add to the challenge of food SCM (Akkerman et al., 2010a; Shukla & Jharkharia, 2013a). The different characteristics also result in issues around product and market differentiation.

Objectives - The logistical objectives in food SCNs differ from objectives in general SCNs (Amorim et al., 2011). In particular, product quality should be added to the more general trade-off between responsiveness (i.e. being able to deliver and adjust according to customer requirements) and efficiency (Akkerman et al., 2010a).

Modelling techniques - Looking at the modelling techniques discussed in the reviews, a distinction can be made between optimisation, simulation and hybrid modelling techniques. Optimisation techniques are used for all types of decision problems (Choi & Sethi, 2010; Melo et al., 2009; Rajurkar & Jain, 2011), though they are most frequently used for network design problems (Kouvelis et al., 2006; Meixell & Gargeya, 2005). Simulation techniques are most frequently used for network control problems (Ahumada & Villalobos, 2011a; Akkerman et al., 2010a). A number of reviews (Chan & Chan, 2009; Ko et al., 2010; Peidro et al., 2008; Zhang et al., 2011) suggest looking into hybrid modelling techniques, e.g. integrating petri nets with other tools, integrating soft computing with more practical algorithms, combining analytical modelling with simulation, etc.

2.4.1 Conceptual research framework

Based on the SCM concepts and relations from the SCM review analysis, a conceptual research framework for floricultural SCN design and control is developed (Figure 2.3). The conceptual framework incorporates the sector-specific context factors that make the decision problems more complex, as well as the multi-dimensional objectives. The framework is used in the next section to build a more detailed view of current SCM research.

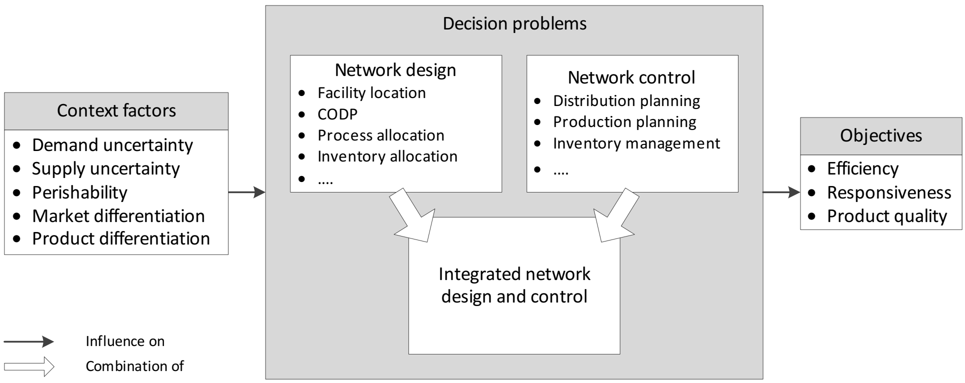


Figure 2.3: Conceptual research framework for floricultural supply chain network design and control

2.5 Literature analysis

The conceptual research framework is used to extract SCM articles that address the decision problems and context factors using a quantitative modelling technique, from a collection of research articles that refer to the literature reviews on which the framework is based. In this way, a representative collection of 71 SCM research articles is constructed for analysis. First, the articles are classified based on the SCM issues they address, i.e. the decision problem that is modelled in the article, e.g. network design (D) or network control (C); the context factors that are incorporated, e.g. perishability (R) or market differentiation (M); the objective of the model, e.g. efficiency (E) or product quality (Q); and the technique that is used, e.g. optimisation (O) or simulation (S). To provide more information on which problems are considered to be network design and which problems are considered to be network control, the categories of decision problems are further split into subcategories like facility location (F) or network flow (N) for network design; production planning (P) or distribution planning (D) for network control; or facility location and distribution planning (FD) for integrated network design and control. The result of the classification is given in Table 2.5. Then, the composition of articles is analysed with respect to problem types on the one hand (Figure 2.4a

Table 2.5: Classification of literature on supply chain modelling, based on conceptual research framework elements and modelling techniques

Reference	Decision problem	Sub category	Context factors	Objectives	Modelling techniques
Amini et al. (2007)	C	S	ER	S	
Lodree & Uzochukwu (2008)	C	P	DR	E	O
Selim & Ozkarahan (2008)	D	FR	M	ER	O
Amaro & Barbosa-póvoa (2009)	C	PD	D	E	O
Bottani et al. (2009)	C	S	R	ER	S
Das & Sengupta (2009)	I	FPD	MD	E	O
Ding et al. (2009)	I	FPD	MD	ER	H
Fonseca et al. (2009)	D	FP	SD	E	O
Gebennini et al. (2009)	I	FPD	MD	E	O
Hammami et al. (2009)	I	FPD	E	O	
Huang et al. (2009)	D	F	ER	O	
Lainez et al. (2009)	I	FPD	P	E	O
Manzini & Bindi (2009)	DC	FD	E	O	
Pathumnakul et al. (2009)	C	P	SR	E	O
Pishvaee et al. (2009)	D	F	SD	E	O
Van der Vorst et al. (2009)	C	S	R	EQ	S
Ivanov et al. (2010)	C	PD	ER	H	
Meuffels et al. (2010)	C	D	E	O	
Monteiro et al. (2010)	D	FT	P	E	O
Nagurney (2010)	D	N	E	O	
Paksoy et al. (2010)	C	PD	E	O	
Pan & Nagi (2010)	D	F	D	E	O
Pishvaee & Torabi (2010)	I	FD	MSD	ER	O
Shimizu & Fujikura (2010)	I	FD	E	O	
Ahumada & Villalobos (2011a)	C	PD	MR	EQ	O
Ahumada & Villalobos (2011b)	C	PD	PSDR	EQ	O
Baboli et al. (2011)	C	I	E	O	
Bidhandi & Yusuff (2011)	D	F	D	E	O
Das (2011b)	D	FI	P	E	O
Das (2011a)	D	F	D	E	O
East (2011)	C	I	R	Q	O
Georgiadis et al. (2011)	I	FPD	D	E	O
Hafezalkotob et al. (2011)	I	FD	D	E	O
Jula & Leachman (2011)	D	N	E	O	
Mestre et al. (2011)	D	FR	R	O	
Papapostolou et al. (2011)	C	PD	E	O	
Pishvaee & Rabbani (2011)	D	F	ER	O	
Pishvaee & Rabbani (2011)	D	F	SD	ER	O
Scholz-Reiter et al. (2011)	C	P	E	O	
Shimizu et al. (2011)	D	FR	D	E	O
Shukla et al. (2011)	D	N	S	E	O
Wee et al. (2011)	C	I	E	O	
Weiler et al. (2011)	D	FR	D	E	O

Continued on next page

Reference	Decision problem	Sub category	Context factors	Objectives	Modelling techniques
Albareda-Sambola et al. (2012)	I	FD	E	O	
Amorim et al. (2012)	C	PD	R	EQ	O
Bashiri et al. (2012)	I	FPD	E	O	
Baud-Lavigne et al. (2012)	D	FP	P	E	O
Chen & Fan (2012)	D	N	E	O	
Chen & Fan (2012)	D	FR	SD	E	O
Contreras et al. (2012)	D	N	E	O	
Creazza et al. (2012)	D	F	E	O	
Egri & Váncza (2012)	C	P	D	E	O
Fahimnia et al. (2012)	C	PD	E	O	
Hall & Saygin (2012)	C	S	D	ER	S
Judd et al. (2012)	D	FR	E	O	
Junqueira & Morabito (2012)	C	PD	E	O	
Kadadevaramath et al. (2012)	C	PD	D	E	O
Karaoglan et al. (2012)	I	FD	E	O	
Kopanos et al. (2012)	C	PD	E	O	
Melo et al. (2012)	D	FI	E	O	
Nickel et al. (2012)	D	F	MD	ER	O
Peidro et al. (2012)	C	PD	ER	O	
Sadjady & Davoudpour (2012)	D	FT	E	O	
Saltini & Akkerman (2012)	C	S	E	S	
Tan & Çömden (2012)	C	P	SD	E	O
Tancrez et al. (2012)	I	FD	E	O	
Thanh et al. (2012)	D	FR	E	O	
Walther et al. (2012)	D	FP	SD	E	O
Wu (2012)	C	D	D	E	O
Yuan et al. (2012)	D	FR	E	O	
Shukla & Jharkharia (2013b)	C	D	R	ERQ	O

Abbreviations:

- Decision problem: C = network control; D = network design; I = integrated network design and control
- Sub category: F = facility location; FR = facility location and resource allocation; FP = facility location and process allocation; FT = facility location and transport mode selection; FI = facility location and inventory allocation; N = network flow; PD = production-distribution planning; P = production planning; D = Distribution planning; I = Inventory management; S = Supply chain performance; FPD = facility location and production-distribution planning; FD = facility location and distribution planning
- Context factors: P = product differentiation; M = market differentiation; S = supply uncertainty; D = demand uncertainty; R = perishability
- Objectives: E = efficiency; R = responsiveness; Q = product quality
- Modelling techniques: O = optimisation; S = simulation; H = hybrid optimisation and simulation

and 2.4b) and context factors, objectives and modelling techniques on the other hand (Figure 2.4c). This will be discussed next. The analysis is finally summarised in Table 2.6 which can then be used to identify research challenges.

The main ***context factor*** that is taken into account in the current literature is *demand uncertainty.* Demand uncertainty is caused by market dynamics, which is related more to market risks in network design (Weiler et al., 2011) and more to price variations in network control (Ahumada & Villalobos, 2011b; Amaro & Barbosa-póvoa, 2009). It is mostly modelled as a (partly) random variable, e.g. normal, Poisson or uniform distributed. However, typical for network design is a scenario approach (Chen & Fan, 2012; Nickel et al., 2012; Pishvaee & Rabbani, 2011; Walther et al., 2012) in which different levels of demand or demand variability are analysed in separate scenarios.

At different levels of decision problems, *market differentiation* is related to different aspects. At the level of network design, it is related to service aspects, e.g. different stock-out rates for different market or customer types (Nickel et al., 2012; Selim & Ozkarahan, 2008). At the level of network control, it is more related to time aspects, e.g. different required lead or delivery times for different market or customer types (Ahumada & Villalobos, 2011a). At the level of integrated network design and control, it is related to time aspects (Ding et al., 2009; Gebennini et al., 2009; Pishvaee & Torabi, 2010), but also to demand-related aspects, e.g. Gebennini et al. (2009) incorporated different demand distributions for different customers, and Das & Sengupta (2009) varied prices over customer types and customer locations.

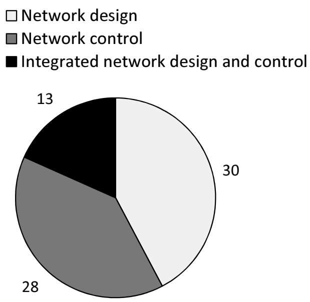
Perishability, the most characteristic context factor for food SCNs, is only incorporated in network control problems, likely due to the dynamic nature of perishability. Perishability is modelled directly or indirectly as fixed shelf life (Ahumada & Villalobos, 2011a; Amorim et al., 2012), linear or exponential decay (Bottani et al., 2009; Lodree & Uzochukwu, 2008; Shukla & Jharkharia, 2013b; Wee et al., 2011), or decay based on biological models (Ahumada & Villalobos, 2011b; Amorim et al., 2012; Pathumnakul et al., 2009). A very different approach is taken by East (2011), in which samples of batches are separated and tested in order to predict the state of the complete batch.

Supply uncertainty is incorporated in food SCN problems and closed loop Supply Chain Network problems, where it is associated with quantity and quality of recoverable or reusable items. Despite the stochastic nature, supply uncertainty is incorporated more in network design problems than network control problems. At the level of network design, research is mostly on closed loop SCNs, where uncertain quantity is modelled as a random variable (Fonseca et al., 2009; Pishvaee et al., 2009; Pishvaee & Rabbani, 2011), and uncertain quality is modelled as an uncertain parameter (Pishvaee et al., 2009). In food SCNs, scenarios are used to represent supply variations (Chen & Fan, 2012; Walther et al., 2012). At the level of network control, research is only on food SCNs, where supply uncertainty is based on production planning models (Tan & Çömden, 2012), incorporating biological models (Ahumada & Villalobos, 2011b) or incorporating environmental and farmer skill influences (Pathumnakul et al., 2009). At the level of integrated network design and control, research is only on closed loop SCNs, where uncertain quantity is modelled as a random variable (Pishvaee & Torabi, 2010).

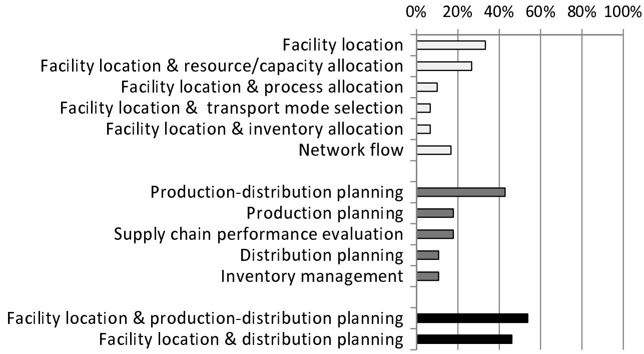
Product differentiation is related to different aspects at different levels of decision problems. At the level of network design and integrated network design and control, it is related to service and time aspects, e.g. different service levels or lead times for different products or product types (Lainez et al., 2009; Monteiro et al., 2010). At the level of network design, it is also related to product mix flexibility (Das, 2011b) and product or component standardisation (Baud-Lavigne et al., 2012). At the level of network control, it is related to perishability, resulting in a differentiation in probabilities of accepting a product based on quality (Ahumada & Villalobos, 2011b).

On the whole, most research is concerned with network design (facility location in combination with flow, capacity, process or inventory allocation, transport mode or supplier selection), closely followed by network control (production planning, distribution planning, inventory management and evaluation of supply chains). When dynamic or stochastic context factors, especially demand uncertainty and market differentiation, are incorporated, integrated design and control (all kinds of integrations of aforementioned network design and control problems) seems to be a more appropriate method.

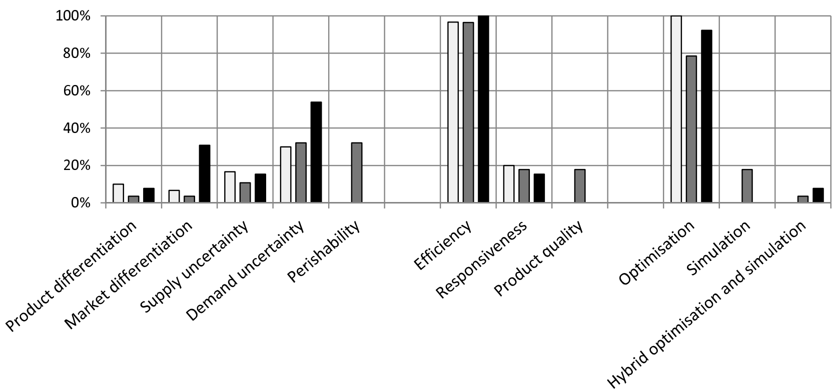
The main ***objective*** used in literature is *efficiency*. Most research is based on costs, or a derivative like profits or margins. Costs that are included are, for example, fixed location costs, capacity costs, production costs, processing costs, holding costs, replenishment costs, shortage costs and transportation costs. Particularly at the network design level, more distinctive cost structures, e.g. taking into account obnoxious effects (Fonseca et al., 2009) or fixed alliance costs (Pan & Nagi, 2010), and more distinctive profit structures, e.g. incorporating exchange rates and quality system costs (Das, 2011a) or (global) taxes (Junqueira & Morabito, 2012), are found. At the network control level more detailed cost and profit structures are found, e.g. adapting profits to price variability (Amaro & Barbosa-póvoa, 2009), using life cycle costing (Wee et al., 2011) and adding food SCN specific costs like harvesting set-up costs (Pathumnakul et al., 2009) and spoilage and energy costs (Amorim et al., 2012). To take into account time aspects at a high level, some network design (Walther et al., 2012) and integrated network design and control problems (Bashiri et al., 2012; Georgiadis et al., 2011; Lainez et al., 2009) look at net present or expected profit values over time. Next to cost-based indicators, other efficiency measures are also used, e.g. utilisation (Amini et al., 2007; Chen & Fan, 2012), production efficiency and recall sizes (Saltini & Akkerman, 2012), and utility functions (Hafezalkotob et al., 2011).



(a) Number of articles per problem type



(b) Specification of problem types



(c) Categorisation by context factors, objectives and modelling techniques

Figure 2.4: Composition of articles specified by conceptual research framework elements and modelling techniques

Responsiveness has two facets: fulfilment and time. Fulfilment has to do with the proportion of demand that can be fulfilled and the number of backorders or shortages. This can be found at the network design level (Nickel et al., 2012; Pishvaee & Rabbani, 2011) and the network control level (Ivanov et al., 2010; Peidro et al., 2012). Time has to do with the time or distance between certain locations and with the comparison between expected and realised delivery times. The first facet of time can be found at the network design level (Huang et al., 2009; Selim & Ozkarahan, 2008), while the second facet of time can be found at the network control level (Hall & Saygin, 2012) and integrated network design and control level (Pishvaee & Torabi, 2010). At the integrated network design and control level, fulfilment and time are also combined (Ding et al., 2009).

In food SCNs *product quality* is an issue, which comes back only at the network control level. Ahumada & Villalobos (2011b) incorporate penalty costs for rejected and discounted shipments, Ahumada & Villalobos (2011a) and Shukla & Jharkharia (2013b) incorporate costs for decay or loss due to transportation, and Amorim et al. (2012) focus on remaining shelf life. Van der Vorst et al. (2009) determine product quality at given points in the supply chain. East (2011) derives cumulative distributions of unacceptable product quality.

In conclusion, a responsiveness objective induces a switch from network control to integrated network design and control. Product quality is only used as an objective when perishability is incorporated, which is only done at the network control level.

The main ***modelling technique*** used in literature is *optimisation*. Most problems are optimised using a (non-)linear programming formulation. In some cases optimal solutions can be found using a solver, in other cases best solutions are found using a heuristic. For network design problems tabu search (Melo et al., 2012), also in combination with network flows (Shimizu et al., 2011), and linear relaxation (Thanh et al., 2012) are used. For network control problems genetic algorithms (Fahimnia et al., 2012), particle swarm approaches (Kadadevaramath et al., 2012), artificial intelligence techniques (Shukla & Jharkharia, 2013b) and approximation algorithms like decompositions (Ahumada & Villalobos, 2011a) and variational inequalities (Nagurney, 2010) are used. When uncertainties have to be incorporated, the (non-)linear programming approaches are substituted by multi-stage stochastic programming approaches for network design problems (Chen & Fan, 2012; Fonseca et al., 2009; Nickel et al., 2012), and possibilistic approaches for network control problems (Paksoy et al., 2010), also in combination with fuzzy methods for integrated network design and control problems (Pishvaee & Torabi, 2010). Uncertainties and dynamics are furthermore incorporated by taking a scenario approach at all decision problem levels. Altogether, the approaches are very diverse. Network design problems are solved using network and graph theoretic approaches (Chen & Fan, 2012; Pishvaee & Rabbani, 2011), robust optimisation (Pan & Nagi, 2010; Pishvaee & Rabbani, 2011) and a label-correcting algorithm (Huang et al., 2009). Shimizu et al. (2011) combine tabu search for location decisions, a graph theoretic approach for allocation decisions, and a scenario planning approach for uncertainties. Network control problems are solved using analytical approaches (Egri & Váncza, 2012; Lodree & Uzochukwu, 2008; Tan & Çömden, 2012; Wee et al., 2011). Fuzzy methods are used for all types of problems (Jula & Leachman, 2011; Peidro et al., 2012; Scholz-Reiter et al., 2011; Selim & Ozkarahan, 2008).

Simulation is only used in a few cases (Amini et al., 2007; Hall & Saygin, 2012; Saltini & Akkerman, 2012; Van der Vorst et al., 2009), and then only at a network control level for supply chain evaluation. Simulation is especially suitable for incorporating complexities for which optimisation is intractable. However, complexities due to the given context factors are only incorporated in two of the cases, Hall & Saygin (2012) incorporate demand uncertainty and Van der Vorst et al. (2009) incorporate perishability. Comparing evaluation (simulation) to optimisation, it is relatively easy to give measures for multiple objectives. Three out of the four studies have, therefore, more than one objective.

In two studies, *optimisation and simulation* are combined. Ding et al. (2009) take an integrated network design and control problem and use a genetic algorithm for optimisation in which objective values are determined by simulation. The addition of simulation makes it possible to incorporate complexities related to market differentiation (different expected lead times for different customers) and demand uncertainty and still get (near) optimal solutions. Ivanov et al. (2010) take a network control problem and use a linear programming model for static optimisation interconnected with a program control model for dynamic elements.

To summarise, the most frequently used modelling technique is some form of mathematical programming. Simulation only appears when tactical or operational decisions have to be addressed in network control or integrated network design and control problems. In a few cases optimisation and simulation are combined in a hybrid approach.

2.5.1 Research challenges

The literature research analysis is summarised in Table 2.6. The studied SCM topics are presented, which at the same time reveals the research gaps, from which in turn Research Challenges (RCs) can be derived. With a reflection on the characteristics, developments and industrial needs of the floricultural sector, four key challenges on the level of design and control of logistics processes for floricultural SCM are defined.

[RC1] Incorporation of product perishability at a network design level

The literature analysis shows that perishability is not often dealt with on a network design level. Typically, next to biological variations, the quality of flowers and plants is determined by time and environmental conditions (such as temperature and humidity during transport). Customers demand guarantees on quality specifications, which leads to strict requirements on the logistics network concepts used in the sector and a need to incorporate product perishability in logistics decisions. Incorporation of perishability is mainly embedded at the network control level, and extending it to the network design level is a notable research direction. Specific issues that could be addressed include:

- Consequences, specifically for product quality, of different transport modes and facility and inventory locations in different parts of the supply chain network;
- Design of responsive supply chains, enabled by increased opportunities for keeping inventory;

- Similarities and differences in network designs for different products with different perishability characteristics.

[RC2] Addition of product quality to efficiency and responsiveness trade-off
The literature analysis shows that there is almost no research that combines efficiency, responsiveness and product quality. One of the main logistics challenges for the sector is to deal with strong dynamics and uncertainty in supply and demand, regarding fresh product quality as well as the available volume in time at a specific place. The sector is characterised by last-minute changes and rush-orders. As a consequence, the required prediction and planning concepts and accompanying logistics system need to be very flexible and responsive. At the same time, costs and efficiency are still the main drivers for the sector, and being able to deliver good product quality is one of the success factors. A multi-objective approach to decision problems, in which a tradeoff is made between efficiency, responsiveness and product quality, is an important research direction. Specific issues that could be addressed include:

- Consequences of different objectives for network design and network control;
- How to exploit (and combine) differentiated logistics requirements of different market outlets on efficiency, responsiveness and product quality;
- How to effectively diversify services using differentiated objectives and logistics requirements.

[RC3] Integrated network design and control
The literature analysis shows that demand uncertainty, market differentiation and responsiveness ask for integration of network design and control. The floricultural sector is subject to demand uncertainty, in product quantity as well as product quality, origin and timing. Furthermore, market differentiation is apparent in different logistics requirements from different sales channels (detail, e-tail and retail). Subsequently, there is a need for responsiveness in floricultural supply chains. It has been shown that these three aspects make integrating network design and control problems in the floricultural sector a promising research direction. Specific issues that could be addressed include:

- Redesign of a logistics network and simultaneous control of inventory and production processes like packaging, bouquet-making, etc.;
- Design of a synchromodal transportation network and simultaneous control of transport routes;
- Consolidation and integration of logistics sub-networks;
- Quality Controlled Logistics (Van der Vorst et al., 2011), i.e. advanced logistics decision-making taking real-time information on product quality behaviour into account, resulting in the delivery of the right product to the right outlet on time at the lowest cost.

Table 2.6: Summary of conceptual research framework elements and modelling techniques that are studied, resulting in research challenges

		Decision problems		
		Network design	***Network control***	***Integrated network design & control***
		Facility location in combination with flow, capacity, process or inventory allocation, transport mode or supplier selection, ...	*Production planning, distribution planning, inventory management, evaluation of supply chains, ...*	*Location-routing, location-inventory, location-allocation with changes over time, ...*
Context factors	***Demand uncertainty***	Modelled in scenarios, arising from risks	Modelled as random variables, arising from varying prices	Modelled as random variables and scenarios RC 3
	Supply uncertainty	Mostly incorporated in design problems, modelled in closed loop SCN research as random variable, modelled in food SCN research as scenarios	Only food SCN research incorporating production and biological models, environment and farming influences	Only closed loop SCN research, modelled as random variable
	Market differentiation	Differentiation in service levels	Differentiation in delivery/lead times	Differentiation in delivery/lead times, demand distributions and prices RC 3
	Product differentiation	Differentiation in service levels, delivery/lead times and standardization	Mostly food SCN research with differentiation in product quality acceptance	Differentiation in service levels and delivery/lead times
	Perishability	RC 1	Incorporating fixed shelf lifes, linear, exponential and biologial decay	RC 1
Objectives	***Efficiency***	Most variation in more distinctive cost/profit structures, using expected or net present values	Incorporating food SCN specific costs and price variability, using life cycle costing	Using expected or net present values
	Responsiveness	As time aspect: measured in distance/time between locations	As time aspect: measured in difference between expected and realized delivery/lead times	As combination of fullfillment and time: measured in % demand fullfilled and difference between expected and realized delivery/lead times RC 3
	Product quality	RC 2	Incorporating costs for quality loss, tracking quality during logistics processes	RC 2
Modelling techniques	***Optimization***	(Non-)Linear programming, stochastic programming, scenario approaches, network and graph theory	Analytical, possibilistic approaches, scenario approaches	Fuzzy methods, scenario approaches
	Simulation		Supply chain evaluation	Supply chain evaluation
	Hybrid optimization & simulation		Linear programming & optimal control theory	Genetic algorithm & supply chain evaluation by simulation RC 4

RC = Research challenge; Boxes with text point to RCs due to limited research being identified; Boxes without text point to RCs due no research being identified

[RC4] Hybrid optimisation and simulation
The literature analysis shows that optimisation and simulation are not often combined in a hybrid approach. Optimisation is mostly used for network design; simulation is mostly used for network control. Just as the integration of decision problems is a research challenge, so is the integration of the applied modelling techniques. Specific issues that could be addressed include:

- Using simulation of operational processes to calculate objective values or parameter values for a strategic optimisation model;
- Using optimisation techniques to find optimal settings for (parts of) a simulation model, to control supply chain systems whilst dealing with supply and demand uncertainty, and perishability;
- Iteratively run optimisation and simulation models, using outputs of one model as inputs for the other model, to design fully optimal supply chain systems whilst dealing with product quality requirements.

2.6 Conclusion

The aim of this research was to create an overview of floricultural sector developments and SCM themes that require further investigation, to analyse current research that addresses those themes and to subsequently define floricultural SCM research challenges from a quantitative modelling perspective. It was found that the main SCM themes and subsequent SCM issues are (1) decision problems: network design and network control; (2) context factors: supply and demand uncertainty, perishability, product and market differentiation; and (3) objectives: efficiency, responsiveness and product quality. A conceptual framework was developed based on these SCM themes and quantitative modelling techniques, which supported identifying the research challenges. It was found that demand uncertainty, market differentiation and perishability are important context factors that serve as drivers for the research challenges. In addition, responsiveness and product quality are important objectives that underlie the research challenges. Furthermore, integration of decision problems as well as integration of modelling techniques is key in the research challenges.

From a management perspective it should be noted that, due to the increased possibilities of keeping inventory and the use of real-time information on product quality, a more responsive supply chain may be created. This means that the current reactive strategy can be turned into a pro-active strategy where managers are familiar with the differences between products and markets and the trade-offs in efficiency, responsiveness and product quality.

As the context factors and objectives are also key in more general perishable SCs, the research challenges will likely not be limited to the floricultural sector. Although this research started from a specific supply chain network, the Dutch floricultural sector can be considered representative for floricultural SCN. The Dutch floricultural sector could serve as a case study in a broader line of research to create a more general perishable SCM framework. Furthermore, this research used documentation both from practice and from science. A more focused research on either practice or scientific literature could add more directed challenges.

In conclusion, the conceptual research framework and literature classification together with the described developments and industrial needs in the floricultural sector show that floricultural SCN research challenges can be found in integrated, quality-driven and responsive network design and control using hybrid optimisation and simulation. Research on the floricultural supply chain network can contribute to perishable product supply chain management due to the comparable and discriminating characteristics of floriculture compared to other perishable products.

Chapter 3

Logistics orchestration in a potted plant supply chain network

De Keizer, M., Groot, J.J., Bloemhof, J., & Van der Vorst, J.G.A.J. (2014). Logistics orchestration scenarios in a potted plant supply chain network. *International Journal of Logistics Research and Applications, 17(2)*, 156–177. doi:10.1080/13675567.2013.837157

Abstract

The Dutch potted plant sector has a dominant international position, but new marketing channels and emerging markets on distance call for new logistics concepts. This chapter explores the potential of an advanced logistics concept, i.e. logistics orchestration, that aims for improved collaboration between supply chain actors. A mixed integer linear programming model is developed to investigate the benefits of logistics orchestration in three scenarios. In these scenarios, the effects of network design and logistics consolidation on logistics costs, working times and CO_2 emissions are quantified. Modelling assumptions and data were validated in collaboration with business partners. Results show that logistics costs, working time and emissions can be significantly reduced by use of a hub network and consolidation. The better the European economic centre can be reached through the hub network, the larger the benefits can be. Embodying a substantial part of European goods flows is required to realise these benefits.

3.1 Introduction

The Dutch floricultural sector is a true 'Diamond' according to Porter (1998); an internationally renowned cluster. Together with a well-functioning transportation cluster it creates a competitive international network. The sector is organised in value chains and clusters where auctions and a large number of small independent growers, traders and logistics service providers work closely together to supply (inter)national markets. We may conclude that the Dutch potted plant sector has a leading position in Europe; in 2011, the Netherlands had a market share of around 50% in EU countries[1]..

In spite of the current leading position for the Dutch, however, there are developments which can harm this strong position in the near future. A first development is that emerging European markets, e.g. in Eastern Europe, are positioned at a greater distance from the Netherlands, which makes it more difficult to reach them efficiently and effectively. A second development is the virtualisation of trading processes (e.g. image auctioning and trader web shops), which decouples these processes more and more from logistics processes, thereby creating an incentive to adapt the logistics processes. Third, new marketing channels become apparent that require increased responsiveness and product diversification. Traders are ordering with a higher frequency, in smaller quantities and with shorter lead times directly from growers, which leads to more transport movements. Fourth, market shares are shifting from small florist shops to large home improvement and garden centres and retail outlets. Examples are German home improvement centres that accomplish more direct trading activities with big Dutch producers and IKEA who is setting up its own supply network. The final major development is the shift of production volumes to other countries. New competitors like Spain, Italy and Poland are entering the arena. These countries are gaining market share very quickly, through providing a wide range of supplied products of good quality and low production costs.

Without innovative action, the Dutch might lose their renowned international position. Stimulating and organising logistics collaboration between different stages in the supply chain network (SCN) regarding network design and consolidation of goods flows, also called as logistics orchestration, may help to prevent this from happening. This research explores effects of horizontal and vertical collaboration by analysing (inter)national logistics orchestration scenarios (LOSs). That is, effective and efficient consolidated distribution scenarios of potted plants to different market segments in which the logistics network configuration and management is optimised and analysed with respect to the three pillars of sustainability (Elkington, 1998): social equity (People), environmental quality (Planet) and economic prosperity (Profit).

[1] http://www.vgb.nl/tiny_mce_upload/Organisatie/Visie/3%20Gematigde%20groei.pdf

This chapter evaluates opportunities and bottlenecks for LOSs in the potted plant SCN using a quantitative modelling approach. Following the taxonomy of Dinwoodie & Xu (2008), we use a case study approach as a validation study and address the following research questions:

- What LOSs are valuable for the European potted plant sector with respect to People Planet Profit issues?
- What recommendations can be proposed regarding the design and implementation of LOSs for the Dutch potted plant SCN?

In Section 3.2, we define logistics orchestration and discuss relevant literature. Section 3.3 presents the case and comes up with the main orchestration scenarios to be evaluated. The model is formulated in Section 3.4 followed by the results in Section 3.5. Section 3.6 discusses lessons learned and presents the main recommendations for logistics orchestration in the potted plant sector.

3.2 Literature review on logistics orchestration

The auction locations in the Netherlands are currently the logistics hubs in the floricultural network. Developments in demand (i.e. expanding to Eastern Europe) and supply (i.e. shift to Southern and Eastern Europe) will move the centre of gravity eastwards. This creates an incentive to redesign the logistics network, thereby incorporating potential hub locations throughout Europe, which can improve the efficiency and effectiveness of the distribution network.

Developments in logistics processes (e.g. increasing transport movements, changing sources and destinations of transport movements decoupling of trading and logistics) will change the flows to and from logistics hubs. This creates an incentive to consolidate flows, which can further improve the performance of the distribution network. Some of the logistical service providers already use consolidation to make use of each other's spare capacity, but this could be enhanced to a wider consolidation throughout the sector, e.g. significant benefits can be achieved by centrally balancing imbalances in inter auction transport (Van Veen & Van der Vorst, 2011).

The above two, logistics network design and logistics consolidation, together constitute logistics orchestration. In the remaining of this section we will review the relevant literature and discuss each of these three concepts.

3.2.1 Logistics network design

An optimal delivery network is intelligently designed to minimise total costs by providing customers the right goods, in the right quantity, at the right place and at the right time. Many factors influence network design decisions, such as geographic shifts in production and consumption, market segmentation, new markets and customer service requirements, cost increases in energy, plant and equipment maintenance, labour, governmental regulation and deregulation, product proliferation and reduced product life cycles. These aspects have contributed to growing demand uncertainty and result in a need for a robust and well-designed SCN (Melo et al., 2009). Sophisticated facility location models are necessary to determine the best supply chain configuration.

Daganzo (2005) divides logistics systems with multiple origins and destinations into distribution systems with or without transhipments. In the case of transhipments, this is carried out at hubs which can have a consolidation (grouping shipments from different origins) or a break-bulk (splitting shipments for different destinations) function. Based on this, Figure 3.1 typifies three main network designs:

- Line network, where each producer has its own transport network to outlets;
- Centralised network, where each producer delivers the goods to a central hub after which goods are sorted and combined for distribution to outlets; and
- Collection and distribution network, especially suited for international networks, where each producer delivers the goods to a central collection hub, after which goods are sorted, consolidated and transported to a distribution hub, where goods are resorted, recombined and distributed to outlets.

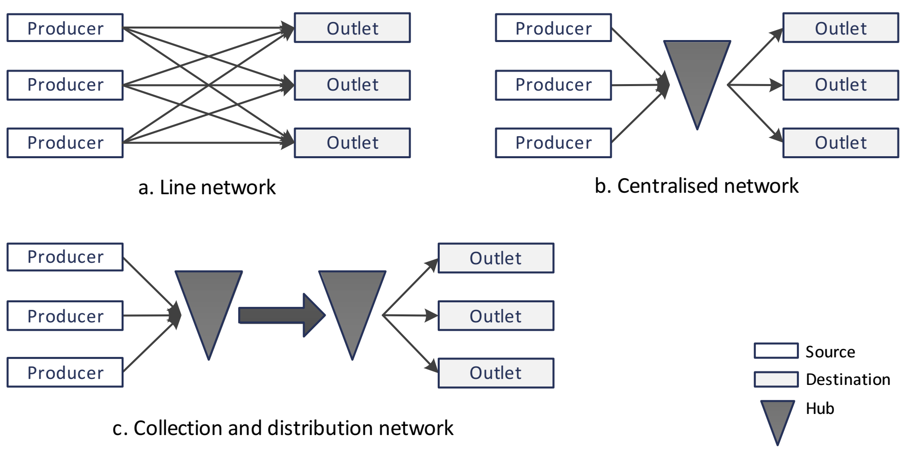


Figure 3.1: Typology of main network designs

In our study, we want to optimise the design of a global SCN, thereby incorporating the routing in supplier and customer regions and analysing multiple objectives. Moreover, we focus especially on the real-life setting of our network design problem.

Quantitative models for strategic design of international supply chains have gained increased importance due to new opportunities for companies to market their products and offer their services all over the world. Meixell & Gargeya (2005) review the appropriateness of existing models to support global SCN design decisions. They conclude that global supply chain models need broader emphasis on multiple production and distribution layers in the supply chain and should include more performance measures to address alternative objectives (such as lead time and service level).

Four years later, Melo et al. (2009) presented an extended review of facility location and supply chain management. Their analysis shows that in order to make facility location models useful in strategic supply chain planning, extensions of existing models are needed, most particularly with respect to multi-layer facilities, multiple commodities, multiple time periods and stochastic parameters. Most of the publications focus on single-period, single commodity, a one or two layer model and combine facility location with inventory and production decisions. Less emphasis has been placed on procurement, routing and choice of transport mode (Melo et al., 2009).

The majority of studies aim to determine a network design with the least total cost (Melo et al., 2009). Little attention has been given to multiple and conflicting objectives, such as resource utilisation, customer responsiveness and sustainability concerns.

The extensive literature review of Melo et al. (2009) results in a list of further research opportunities in the network design area, such as the inclusion of uncertainties, the impact of postponement decisions and associated difficulties with filling customer orders on time and profit-oriented objective functions with revenue management ideas. An addition to this is the integration of tactical or operational decisions in network design (e.g. determining facility locations and expansions as well as production and distribution planning) which makes the network design model capture more of real-life complexity (Bashiri et al., 2012).

The network design problem is well understood at the technical level, but translating it to practice is still difficult. Meixell & Gargeya (2005) suggest investigating more industry settings in the context of global supply design. Dealing with real-life complexity, service level constraints and data mapping can help to lower the practical obstacles to network design (Creazza et al., 2012).

According to Dekker et al. (2012), attention to the environmental aspects of SCN design, and especially facility location, is increasing considerably. Using metrics, often a measurement of emissions, the environmental effect can be made clear and different alternatives can be compared. A good example of this can be found in Van der Vorst et al. (2009), which shows that fresh produce supply chain network (FSCN) design should be aimed at logistics performance as well as environmental sustainability and product quality. The review of Akkerman et al. (2010a) shows that the consideration of People and Planet issues in designing FSCNs is limited. The social dimension is particularly under-researched, possibly due to the fact that it is harder to quantify.

3.2.2 Logistics consolidation

One of the key aspects in our study is effective and efficient consolidated distribution of potted plants. Consolidated distribution can improve logistics performance, e.g. increasing capacity utilisation by combining less than truck loads when the volume of the goods to be distributed is smaller than the transport unit size or decreasing total travelled distance by splitting and recombining full truck loads based on sources and destinations of the goods to be distributed. Consolidation is often needed when the delivery frequency is increased with a resulting decrease in delivery batch size.

There are three types of consolidated transportation (Ghiani et al., 2004):

- Temporal consolidation, this means that goods which are scheduled for transport at different times are now transported together in a transport unit at the same time;
- Facility consolidation, this means that goods which have different destinations are now transported together in a transport unit for (part of) the route; and
- Product consolidation, this means that goods with different characteristics (e.g. chilled and frozen or potted plants and vegetables) are transported together in a transport unit.

If transport flows are consolidated at a distribution centre without storage, then this is called cross-docking. This concept is most beneficial for flows that have a high margin, a high value density, a low packing density or a limited shelf life (van Damme, 2005). Therefore, it is a valuable concept for potted plants.

Consolidation should lead to more efficient transport in the sense that it should lead to a reduction of total number of transport kilometres. This can be achieved by a reduction in transport distance (by optimal route planning) and/or a reduction in transport movements (by optimal truck capacity utilisation). Clearly, more efficient transport is beneficial for reduced environmental pollution and preserved quality of (perishable) goods due to reduced lead times.

3.2.3 Logistics orchestration

Consolidated distribution requires a specific network design of sources (departing points), routes and sinks (destinations). This can only be optimised with a sufficient level of coordination or orchestration within the SCN. Based on the literature on network coordination (e.g Bijman et al., 2006), we can distinguish three levels of network orchestration (Figure 3.2):

- horizontal orchestration, which implies that logistics activities conducted by multiple actors at the same stage in a supply chain are orchestrated (often by a logistics service provider). An example is the coordinated transport of different suppliers to a central hub or the coordinated transport from a distribution hub to different customers.

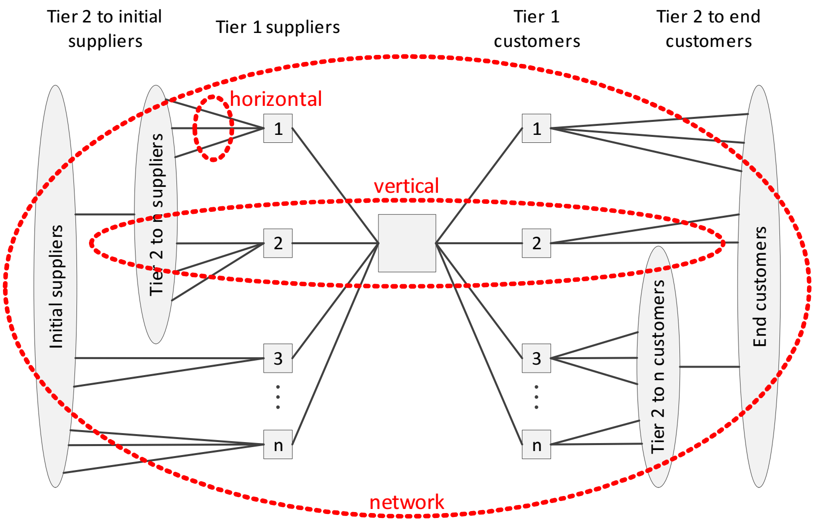


Figure 3.2: Levels of logistics orchestration (dotted lines indicate scopes of levels)

- vertical orchestration, which implies that logistics activities conducted by actors at multiple stages in a supply chain are orchestrated. For example, the activities from initial supplier to end customer, including the in-between stages.
- network orchestration, which implies total orchestration of logistics activities of multiple suppliers, multiple customers, multiple product types and thus multiple supply chains.

A network orchestrator is responsible for configuring the logistics network such that customer and network member preferences are satisfied. Network members together carefully plan how capacity should be created throughout the system and decide jointly where and in what quantities inventories of various types should exist (Stadtler, 2005). Moreover, they must also decide in advance what actions will be taken when various unplanned events occur. Thus, strategic and tactical plans must be created simultaneously to achieve maximum system effectiveness and robust performance.

In the strategic and tactical optimisation of distribution networks, Van Duijn & Kreutzberger (2006) distinguish a number of critical decision variables, such as distribution unit size (e.g. pallets versus rolling containers), transport mode and unit size (e.g. using short sea transport or larger truck sizes), frequency of transport, distribution volume and distribution network design. These decision variables relate to logistics orchestration, i.e. network design and consolidation, and indicate opportunities for improved logistics orchestration.

Network design in logistics orchestration leads to centralisation, which, in a system with a large volume of goods, can improve environmental performance without compromising customer service (Kohn & Brodin, 2008). Furthermore, centralisation enables consolidation which has a proven positive impact on CO_2 emissions as well as costs. For example, centralisation can decrease emergency deliveries and shipment consolidation can enable a change in transport mode, which is beneficial not only from an economic viewpoint but also from an environmental viewpoint. All in all, the objective of SCN design is shifting from just Profit issues to People Planet Profit issues and logistics orchestration can contribute to this objective.

3.3 The potted plant supply chain network

This section describes the case study design and the specific characteristics of the potted plant SCN. Furthermore, three LOSs are presented that will be analysed to evaluate logistics orchestration benefits.

3.3.1 Case study design

Sector partners (auctions and trading organisations) and research institutes worked together to identify and target the main opportunities and threats for the floricultural sector. Process analyses were used to determine the characteristics of the sector, to collect relevant data and to identify future developments. The analyses, together with the literature review on orchestration, resulted in a shared view on possible LOSs for which the effects on logistical performance seemed interesting to quantify. In close cooperation with the sector partners, a sensible demarcation of the potted plant sector was agreed upon, relevant parameters were identified, data were collected and the model presented in this chapter was formulated. On a regular basis, the refined data and the results from preliminary analyses were presented to the sector partners to validate the assumptions and to focus the research scope.

3.3.2 Characteristics of the potted plant Supply Chain Network

The SCN of the Dutch potted plant sector consists of the following links (Figure 3.3):

- domestic and foreign potted plant growers that produce potted plants with a value of €2340 million, of which some €2 million (around 85%) comes from about 1360 Dutch potted plant growers that produce about 500 different sorts of plants on a total area of 1930 ha;
- one main auction Flora Holland created through a merger between the Dutch auctions Flora Holland and VBA in 2008. This provides trading facilities at six locations in the Netherlands for trading in cut flowers (about 70% of turnover) and potted plants (about 30%);

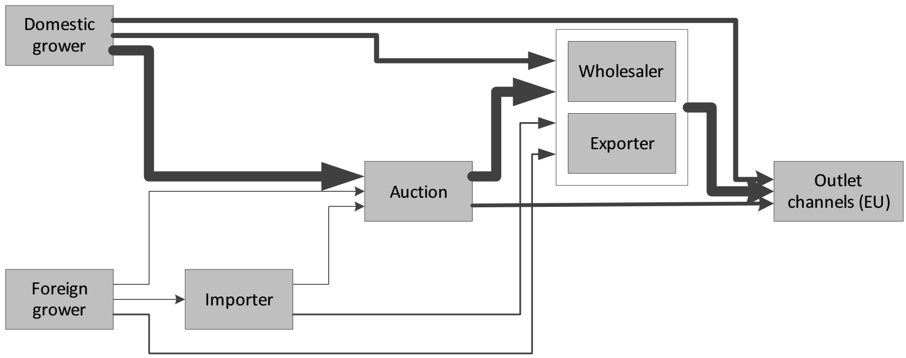


Figure 3.3: The potted plant supply chain network (line width indicates importance of flow in total flow)

- about 1200 traders that can be split up into three groups: wholesalers, exporters and importers;
- transport between two links is often outsourced to one of the 70 logistics service providers. In some cases, these providers execute additional activities such as quality control, handling and packaging; and
- different outlet channels in national and international market places: florist's shops, supermarkets, discounters, garden and home improvement centres and market and street trade.

The Dutch Floricultural Industry is operating on a global scale with an increasing international turnover. Total export of potted plants in 2011 was 2039 million Euros. The three main markets are Germany (50% market share), the UK (52%), and France (33%). Export demand is satisfied both from Dutch production and imported products. Imported products accounted for 18.5% of the exports in 2010 and had grown quickly in value reaching €377 million in 2010 from a 2005 value of €278 million. The main European sourcing countries currently are Germany, Belgium, Italy, Denmark and Spain. If we focus on different market regions, we can identify some differences and trends. In 2011, total export volume of potted plants to Germany decreased by 1.6%. This decline is mainly caused by the decreasing volume share of supermarkets (27% market share), accompanied by a stable number of florist shops (14% market share). In the UK, the potted plants business increased (9.3%), mainly via supermarkets whose market share increased from 38% in 2008 to 45% in 2011. Finally, the export to France increased (by 1.7%), due to the increasing market share (20%) of florist shops which remains the largest category of outlet in France.

Changing consumer requirements, new legal restrictions, foreign competitors that penetrate the market with new value propositions, infrastructural problems, such as traffic jams, virtualisation and so on, have stimulated Agri-Food SCNs to innovate their network structures, business processes and products (Van der Vorst et al., 2005). The complexity and dynamism has increased significantly over the years and will increase in years to come. This will result in new actors that will enter the playing field, new ways of managing and coordinating processes and use of new technologies to support management decision-making. Furthermore, businesses have to respond to the request for value-adding products by delivering a service concept (that is a product including all kinds of services such as background information on the product) instead of just a basic product. The search for partners that add value to products is crucial, which means networks are not per se stable; every network is subject to a degree of dynamism resulting in partner shifts as new objectives are strived for. In general, it is clear that future competitiveness will require more collaboration in the potted plant SCN together with differentiated marketing channels. Logistics orchestration might well be part of the solution.

3.3.3 Logistics orchestration scenarios

The LOSs are based on (combinations of) two possible chain performance improvement directions in network orchestration as discussed in Section 3.2: enhanced logistics network design (use of a hub network) and logistics consolidation (in collection of products and in distribution to points of sale). Consolidation leads to performance improvement due to better utilisation of truck capacity and more efficient routing. Currently, more and more transport is carried out by logistical service providers, showing that more efficiency is obtained if logistical planning can be applied to a larger network of producers and outlets. The enhanced network structure contributes to the chain performance by facilitating a better match of production and demand and a higher responsiveness. An enhanced network design implies a shift from a line network (Figure 3.1(a)) to a centralised network (Figure 3.1(b)) or a collection and distribution network (Figure 3.1(c)).

Summarising, the following decision variables have to be considered: the number of hubs, the hub locations and the degree of consolidation. To investigate the influence of enhanced network design and consolidation the following LOSs are defined (Figure 3.5):

LOS 0: Current situation – This scenario resembles the current potted plant distribution configuration for Europe. Products are transported from producers to consumers without the use of hubs. One part of the total product volume demanded for in the market places is transported directly between countries (denoted as direct deliveries), and this volume is based on import and export figures. The remaining product volume is sourced and delivered locally (denoted as local-to-local). Figure 3.4 shows the product flows in this situation.

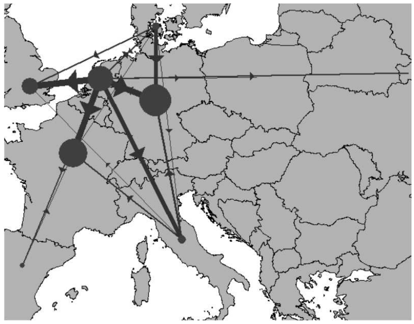


Figure 3.4: Current flows in the potted plant SCN (sizes of circles indicate local-to-local volume per country, widths of arcs indicate direct delivery volumes between countries)

Products are transported from a supplier region to a customer region without consolidation. This means that different types of suppliers (suppliers are either independent growers or they are associated to a grower organisation) and different types of customers (customers are classified into seven types: florist shops, supermarkets, market and street trade, garden centres, home improvement centres, growers and other) do not cooperate. Suppliers or customers of similar type, however, can cooperate to transport their production or demand.

LOS 1: Use of hubs – In this scenario, distribution hubs are introduced in the network. Now, instead of direct deliveries and local-to-local flows, all products are transported via European hubs. This means that products are gathered at a hub and are then distributed to outlets or they go through another hub after which they are distributed. Three hubs are prescribed; these are the three main Dutch trade locations. A further 14 hubs are optional; these are potential hub locations determined via a gravity point analysis of (future) European supply and demand. So, in total there are 17 potential hub locations.

As in LOS 0, products are transported from a supplier region to a customer region without consolidation, i.e. this is only cooperation between suppliers or customers of a similar type.

LOS 2: Consolidation – In this scenario, consolidation is introduced. As in LOS 1, there are 17 hubs (three prescribed and 14 optional) through which the total product volume must be transported. However, now transport of products includes consolidation. This implies that different types of suppliers, or different types of customers, coordinate their logistic activities. One can choose whether all types work together or only a subset. If consolidation takes place it is assumed that all point-of-sale outlets are delivered with the same frequency and that a higher degree of truck utilisation is possible for the regional collection and distribution.

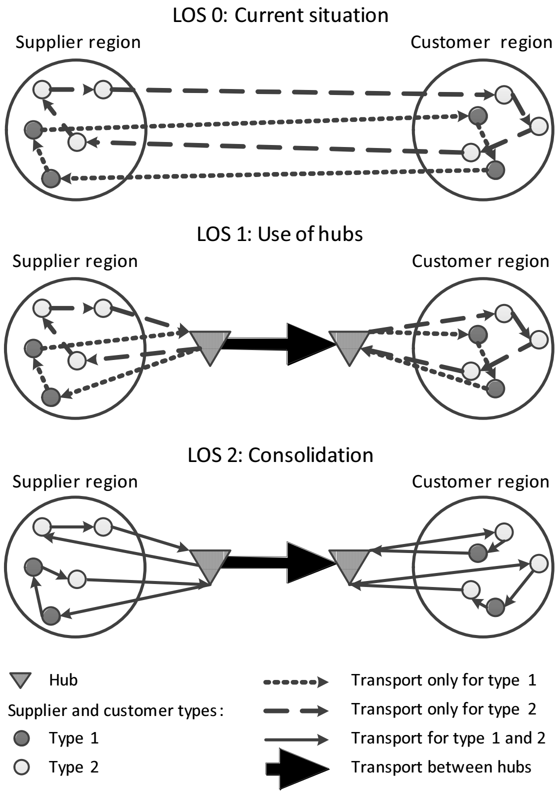


Figure 3.5: Logistics orchestration scenarios (LOSs)

3.3.4 Case demarcation and assumptions

In collaboration with our project partners, several assumptions were defined to demarcate the potted plant distribution in Europe in such a way that input data is obtainable, reliable and contains sufficient level of detail for meaningful analysis of the research questions being addressed.

Supply and demand

The European market is narrowed down to nine countries representing 85% of the market volume. The Netherlands, Germany, France and the UK are the main producers and the main consumption markets. Russia and Poland are the most important upcoming consumption markets and Denmark, Italy and Spain are additional and upcoming producers. Approximately, 62% of the volume consists of locally produced and locally consumed plants, with the remaining 38% of the volume catered for by trade between

Table 3.1: Direct delivery and local-to-local figures per country for the current situation

	Direct deliveries		Local to local	
	Direct export from named country to other countries		Locally produced and consumed products within a country	
	Product value (mln €/year)	Share of total product value	Product value (mln €/year)	Share of total product value
Netherlands	1106	27%	400	10%
Germany	55	1%	1050	26%
Italy	136	3%	132	3%
Spain	46	1%	88	2%
France	14	0%	460	11%
Poland	3	0%	13	0%
Russia	0	0%	19	0%
UK	2	0%	263	6%
Denmark	180	4%	129	3%
Total	1542	38%	2554	62%

the various countries. Table 3.1 provides an overview of 'direct delivery' (i.e. direct export from one country to another) and 'local-to-local' (i.e. local transport within (a region of) a country) for LOS 0.

The potted plants are divided into three types:

- Green: live indoor plants and cacti (excl. rooted cuttings, young plants and flowering plants with buds or flowers);
- Flowering: indoor flowering plants with buds or flowers (excl. cacti);
- Bed: live perennial outdoor plants incl. their roots.

From production, import, export and consumption figures, a matching set of yearly supply and demand volumes per plant type is constructed. The figures are given in product values and scaled to the export market value, which is necessary given the unknown and variable margins in consumption figures, to obtain a closed system of supply and demand. If available, exact figures on production and consumption including a division over plant types are used; otherwise estimations are made, for example, based on number of inhabitants or the import and export divisions for each plant type.

To capture the regional aspect of production and demand, each country is divided according to the NUTS-2 regions (Nomenclature of Territorial Units for Statistics, NUTS-0 corresponds to countries, NUTS-1 corresponds to a division in north, middle and south and NUTS-2 corresponds to a division comparable to Dutch provinces or German Bundesländer).

Hub locations

The hub locations are pre-chosen based on the following criteria: besides the three current Dutch locations, hub locations close to or in the main residential areas in Europe are chosen (Germany, the UK and France) and hub locations close to upcoming areas of production (Spain and Italy) and consumption (Russia) are chosen. The costs of the hubs are assumed to be equal for all hubs in Europe. When a hub is used a minimal area of 5000 m^2 is assumed.

Chain performance indicators

In the LOSs, different collection and distribution systems (i.e. different network structures and levels of consolidation of product flows) with different levels of customer service and responsiveness are compared on logistics costs (Profit), working time needed to distribute all products (People) and global warming potential (GWP; Planet). Optimisation is based on logistics costs in which also work shift duration, regionally given congestion (traffic jams), and activity duration are taken into account. GWP is measured in CO_2 equivalents and calculated similar to Chaabane et al. (2012). As we have only one transport mode (trucks), we convert kilometres to CO_2 equivalents using a classification factor.

3.4 Model formulation

The structure for the potted plant SCN is a multi-level system of facilities from different supplier regions, to hubs, to different customer regions. Transportation costs are a significant part of the total costs, so the spatial configuration of the network and, therefore, the location decisions are critical decisions for the system. To be able to evaluate, the different LOSs for Europe a location– allocation model, formulated as a mixed integer linear programming (MILP) model, is used. The differences in the LOSs are incorporated in the calculation of the transport cost parameters of the MILP.

Figure 3.6 shows the inputs, parameters, outputs and key performance indicators (KPI's) required to evaluate the LOSs with the MILP model.

3.4.1 Location allocation model

Indices:

s	supplier region ($s = 1, 2, \ldots, S$)
h, h'	location of hub ($h, h' = 1, 2, \ldots, H$)
c	customer region ($c = 1, 2, \ldots, C$)
p	product type ($p = 1, 2, \ldots, P$)

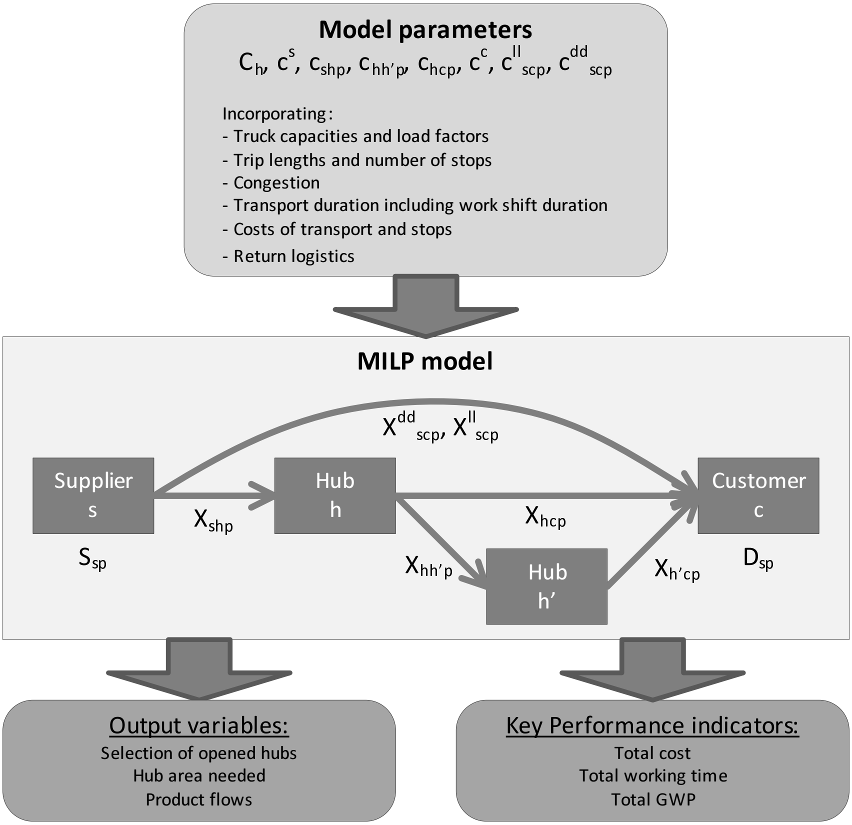


Figure 3.6: Model overview

Decision variables:

$Y_h \in \{0,1\}$	opening a hub on location h or not
$X_{shp} \geq 0$	flow of product type p transported from supplier region s to hub h
$X_{hh'p} \geq 0$	flow of product type p transported from hub h to hub h'
$X_{hcp} \geq 0$	flow of product type p transported from hub h to customer region c
$X^{ll}_{scp} \geq 0$	local-to-local (ll) flow of product type p transported from local supplier region s to local customer region c
$X^{dd}_{scp} \geq 0$	direct delivery (dd) flow of product type p transported from supplier region s directly to customer region c

Parameters:

C_h	costs to use hub h (€)
c^s	costs to collect all products from all suppliers in all supplier regions (€)
c_{shp}	costs to transport product type p from supplier region s to hub h (€)

$c_{hh'p}$	costs to transport product type p from hub h to hub h' (€)
c_{hcp}	costs to transport product type p from hub h to customer region c (€)
c^c	costs to distribute all products to all outlets in all customer regions (€)
c^{ll}_{scp}	costs to transport product type p from local supplier region s to local customer region c (€)
c^{dd}_{scp}	costs to transport product type p from supplier region s directly to customer region c (€)
S_{sp}	supply volume in supplier region s of product type p (€)
D_{cp}	demand volume in customer region c of product type p (€)
r_h	rent per m^2 of hub h (€/m^2)
α	factor to relate the volume of the flow through a hub to the area needed to handle the volume (m^2/€)
M	big number

The calculation of the transport cost parameters is explained in Section 3.4.2. The location-allocation model is formulated as follows:

$$\begin{aligned}\min \quad & \sum_h C_h Y_h + \sum_h r_h \frac{\sum_s \sum_p X_{shp} + \sum_{h'} \sum_p X_{h'hp}}{\alpha} \\ & + c^s + \sum_s \sum_h \sum_p c_{shp} X_{shp} + \sum_h \sum_{h'} \sum_p c_{hh'p} X_{hh'p} \\ & + \sum_h \sum_c \sum_p c_{hcp} X_{hcp} + c^c + \sum_s \sum_c \sum_p c^{dd}_{scp} X^{dd}_{scp} + \sum_s \sum_c \sum_p c^{ll}_{scp} X^{ll}_{scp}\end{aligned} \tag{3.1}$$

$$s.t. \quad \sum_h X_{shp} \leq S_{sp} \qquad \forall \text{s,p} \tag{3.2}$$

$$\sum_h X_{hcp} = D_{sp} \qquad \forall \text{c,p} \tag{3.3}$$

$$\sum_s X_{shp} + \sum_{h'} X_{h'hp} = \sum_{h'} X_{hh'p} + \sum_c X_{hcp} \qquad \forall \text{h,p} \tag{3.4}$$

$$\sum_s \sum_p X_{shp} + \sum_{h'} \sum_p X_{h'hp} \leq M \times Y_h \qquad \forall \text{h} \tag{3.5}$$

The objective function (3.1) minimises the costs of using and renting the open hubs, as well as the costs of collection of all products, of transport from the suppliers to the hubs, of transport between hubs and of transport from the hubs to the customer regions, the costs of distribution, the costs of direct deliveries and the costs of local-to-local deliveries. Equation (3.2) makes sure that for every supplier region and every product type no more is transported than produced. Equation (3.3) ensures that demand from a customer region is fulfilled, for every product type. Equation (3.4) balances the flows entering a hub from the supplier regions and other hubs, with the flows leaving a hub, to the customer regions and other hubs, for every hub and every product type. Equation (3.5) assures that there is only flow through a hub when it is open. In specific LOSs sometimes additional constraints are used, such as the constraint that a certain number of hubs is required, or that only part of the volume is available for distribution in the European network (Table 3.2), etc.

Table 3.2: Volume constraints in different LOSs

	X_{shp}	$X_{h'hp}$	X_{hcp}	X^{dd}_{scp}	X^{ll}_{scp}
LOS 0	$= 0$	$= 0$	$= 0$	≥ 0	≥ 0
LOS 1	≥ 0	≥ 0	≥ 0	$= 0$	$= 0$
LOS 2	≥ 0	≥ 0	≥ 0	$= 0$	$= 0$

3.4.2 Logistics costs calculation

The different parameters in the model are calculated based on the logistics characteristics of the potted plant sector and have been validated by experts from that sector. Different levels of orchestration and different fractions of deliveries via hubs, direct deliveries and local-to-local deliveries in scenarios lead to different parameter values. Therefore, we explain the parameter calculations here in more detail (mathematical formulations can be found in the appendix).

Collection and distribution of products

The total costs to collect all products from all suppliers in all supplier regions, c^s, is the sum of the number of trips times the costs of a trip for every supplier region and every supplier type. The number of trips follows from the volumes to be transported (total volume minus the volumes for direct and local-to-local deliveries) converted to the necessary truck space, from this taking the fraction of the specific supplier type within the region and then dividing by the supplier type specific amount that fits into one truck. The supplier type and region specific costs of a trip are calculated as the sum of the length of a trip times the costs per kilometre and the number of pick-ups times the costs per pick-up. The length of a trip is an estimation based on the distance from the centre to the border of a region and on the delivery frequency and the number of suppliers in a region.

The costs to distribute products to satisfy the customer demand within a region, c^c, are calculated with the same logic. Additionally, in the costs per trip, which are customer type and region specific, costs related to cross-docking are included (cross-docking emerges when a supply chain contains echelons between hubs and customers, e.g. a wholesale market where flower shops can buy their products). The supply chains corresponding to different customer types have different properties. Every supply chain makes its own balance between efficiency (costs) and service (responsiveness). A supermarket or home improvement centre will focus more on efficiency compared to a flower shop. These issues are incorporated in the calculation of the distribution costs through parameters such as delivery frequency and number of customers.

Transport of products from suppliers to hubs to customers

The costs of transport from supplier regions to hub locations, c_{shp}, are defined based on the costs of a truck and the number of trucks needed. The required transport time between supplier region and hub location depends on legislation regarding the duration of work shifts and also takes into account possible congestion in the supplier and hub regions. Moreover, the possibility of return logistics can be taken into account by adjusting the return logistics factor. The total transport time needed is converted to costs and divided by the number of trucks needed to transport the relevant amount of products. The number of trucks needed is calculated by the truck capacity times its load factor, corrected for the space factor of the various product types.

The same logic is applied to calculate the transport costs between hubs, $c_{hh'p}$, and the transport costs from hubs to customers, c_{hcp}.

Direct and local-to-local deliveries

The logistics costs related to the direct and local-to-local deliveries are the sum of the costs to collect the supply from supplier regions and distribute the demand to customer regions (similar to the method outlined in Section 3.4.2) and the transport costs between the regions (similar to Section 3.4.2) using the appropriate data.

3.5 Results

The current situation (LOS 0) is taken as the benchmark and the KPI's (costs, time and GWP; where time and GWP are calculated with the same logic as the costs) for this scenario are set to 100. The KPI's resulting from different LOSs are subsequently related to the benchmark. Next, a breakdown of the KPI's by supply chain segments is given for different levels of consolidation to identify crucial segments. Furthermore, a sensitivity analysis is performed on the flows available in the network to identify the minimum requirements to constitute an LOS that is both efficient and sustainable. To find out whether there is a gradual development path, a sensitivity analysis is performed on the number of hub locations that can be opened. This is done for current volumes in the network and for expected future volume trends, which then simultaneously assesses robustness of the network design.

Table 3.3: Normalised KPIs for different LOSs

	Hubs	Normalised KPIs		
		Costs	Time	GWP
LOS 0	-	100	100	100
LOS 1	15	81	73	91
LOS 2	15	72	62	80

3.5.1 Effects of logistics orchestration scenarios

Effects of the different parts, network design and consolidation, of LOSs can be seen in Table 3.3. It shows that simply redesigning the network, LOS 1, gives a 19% decrease in costs. This is mainly due to time savings because long transportation routes in the current situation are split into routes to and from a hub, resulting in fewer violations of work shift durations. Consolidating flows leads to a further 9% cost decrease, due to a better load factor of trucks, resulting in less truck kilometres, and thus CO_2 emissions, and transport time.

Figure 3.7 shows the flows from suppliers to hubs to customers in the optimal hub network for LOSs 1 and 2 (the optimal hub network is the same in both scenarios). Instead of distributing from the Netherlands, as in the current situation (Figure 3.4), three hubs in the Netherlands and as many as 12 others across Europe create the most efficient network.

To show the responsiveness of the hub network, Figure 3.8 shows the average time needed to travel from a supplier or customer to the nearest hub per country. It is beneficial to focus on providing particularly good service to the most important countries for supply and demand (e.g. the Netherlands, Germany and the UK), making responsive service to small countries with smaller demand and supply volumes (e.g. Russia) a less important consideration.

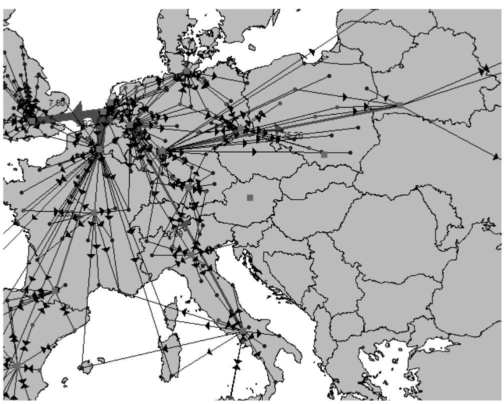


Figure 3.7: Optimal European hub network

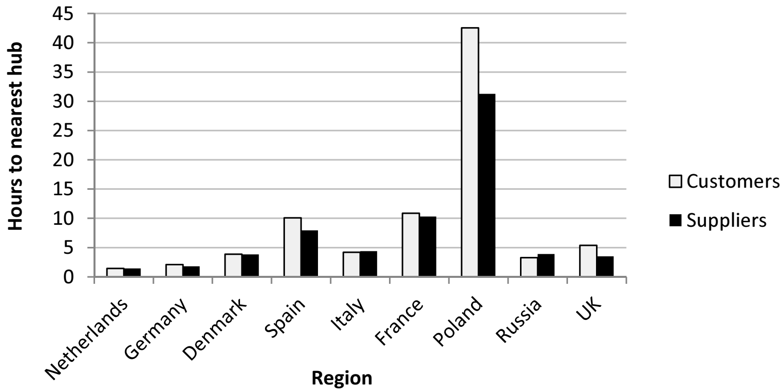


Figure 3.8: Responsiveness of suppliers and customers in a European hub network

3.5.2 Crucial segments at different levels of consolidation

When we allocate the total costs to different segments in the network (Table 3.4) in the scenario where we have no consolidation, the distribution of products in customer regions accounts for the largest share and the collection of products in supplier regions takes the second largest share. Consolidation of collection or distribution both significantly decrease costs in supplier regions and customer regions, respectively. However, in every situation the distribution from hubs to customer regions accounts for more than half of the costs, and therefore consolidation of distribution has a larger benefit than consolidation of collection. Consolidating all collection and distribution is a huge challenge because of the collaboration that is needed between all European actors. Therefore, we also present results for consolidating only the collection from Dutch suppliers and the distribution to retail outlets (the number of retail outlets is limited which eases collaboration). Due to the small distance from the Dutch suppliers to the Dutch hubs and the German suppliers taking a very large share of total supply, consolidating only in the Netherlands does not result in a significant decrease in kilometres and time. The rather high load factor of trucks to the retail outlets limits the opportunity for consolidation in this part of the network. Consequently, consolidation at a higher level is needed to gain really major benefits.

3.5.3 Available flows needed for sustainable orchestration

In LOS 2, we assume that all direct deliveries and local-to-local flows from LOS 0 are transported via a European hub network. In Table 3.5 we show the number of hubs and KPIs when only local-to-local flows are available for the European hub network and when only direct delivery flows are available for the European hub network. This shows that direct delivery flows form the foundation that is needed to constitute an

Table 3.4: Cost share of different network segments for different levels of consolidation

	Cost index	Cost shares				
		Supplier region	Supplier to hub	Hub to hub	Hub to customer	Customer region
No bundling (LOS 1)	81	26%	16%	8%	22%	28%
Bundling collection & distribution (LOS 2)	72	22%	18%	9%	25%	26%
Bundling distribution	77	27%	17%	8%	24%	24%
Bundling collection	76	21%	17%	8%	24%	30%
Bundling collection & distribution	72	22%	18%	9%	25%	26%
Bundling collection NL	80	25%	16%	8%	23%	29%
Bundling retail distribution	80	26%	16%	8%	23%	27%

efficient hub network, as without that volume the foundation costs, working time and CO_2 emissions are close to the performance of the current network. The density of the hub network is determined by the local-to-local flows for which 14 hubs are selected as opposed to nine hubs for direct delivery flows.

3.5.4 Hub development path and robustness

Current volumes

In the optimal solution for LOS 2, 15 out of 17 hubs are opened. In Figure 3.9 we show the indices of KPI's when we limit the maximum number of hubs that can be opened. We start with a limit of three hubs, because we assume the hubs in the Netherlands will always be used, and we end with a limit of 15 hubs, because this is the optimum. Results show that only five hubs are needed to outperform the current situation (intersection one, where the costs line crosses the reference of 100).

When we allow for only three hubs, distance and distribution time are very high compared to the current situation, because large detours to just a few hubs in the Netherlands do not compensate for the aggregation of flows. With each hub that is added detours become smaller and the benefit of using hubs increases. Most notably, distribution time decreases because violations of work shift durations decrease due to long routes being split up into short routes to hubs, between hubs and from hubs. Time outperforms the current situation after just four hubs (intersection two), while CO_2 only outperforms the current situation after 11 hubs (intersection three).

The patterns for LOSs 1 and 2 are the same, only for LOS 2 the performance on the KPI's is lower due to suppliers and outlets working together, which makes the intersection points shift to the left.

Table 3.5: Hubs and normalised KPIs with different available flows in a consolidated hub network

	Hubs	Normalised KPIs		
		Costs	Time	GWP
Both local-to local and direct delivery flows are consolidated and transported via hubs	15	72	62	80
Only local-to-local flows are consolidated and transported via hubs	14	98	91	100
Only direct delivery flows are consolidated and transported via hubs	9	74	68	85

When we look at the locations of the hubs, there is a gradual path of development. At first, hubs are opened in the centre of Europe and once the centre is covered hubs in the east and south of Europe are opened. There is no difference in locations between LOSs 1 and 2, which indicates that consolidation does not change the location of hubs for the selected parameter settings.

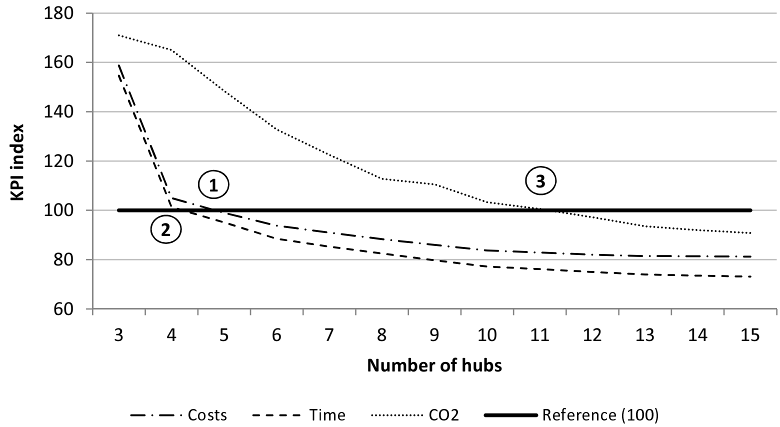
Future volumes

The volumes of the flows are expected to change over the years due to supply and/or demand growth or decline. In particular, production in Southern Europe and demand in Eastern Europe are expected to grow in the future. In addition, a market shift from detail shops (i.e. florists, market and street trade) towards larger retail outlets (i.e. supermarkets, discounters and garden and home improvement centres) is expected. Table 3.6 shows the difference in volumes and KPI's for the current and future supply and demand states. If product volume grows by 29%, costs increase by almost 60%. The non-profit KPI's increase even more; working time increases by around 70%; and CO_2 emissions increase by almost 90%. This is due to the fact that local-to-local flows are growing, for which the hub network is less beneficial.

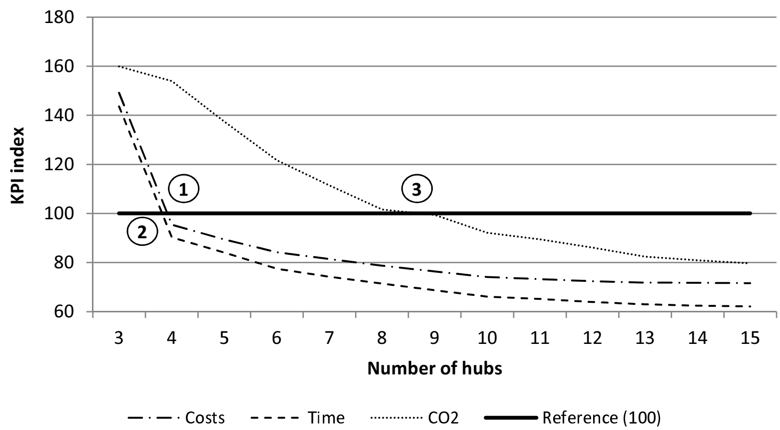
When we again look at the locations of the hubs, the development path in the future situation is not as gradual as for the current situation. Additional hub locations are opened alternately in east and south Europe, until there is a sufficient spread of hubs across the continent. In the end, the designs for the current and future situations are very similar except that one hub becomes redundant in the future situation.

Table 3.6: Hubs and KPIs for supply and demand growth

	Volume	Hubs	Normalized KPIs		
			Costs	Time	GWP
Current state	100	15	72	62	80
Future state	129	14	114	107	150



(a) KPI's for LOS 1



(b) KPI's for LOS 2

Figure 3.9: KPI's for different numbers of hubs

3.6 Conclusion and discussion

A multi-layer, multi-product location–allocation model for the European distribution of potted plants has been developed as an instrument with which to investigate the effects of logistics orchestration. The most challenging part in developing the model was found to be collecting and processing a reliable and realistic data set. Using this model, the effects of enhanced network design (use of a hub network) and network consolidation (in collection of products and in distribution to outlets) on logistics costs and customer responsiveness are quantified and the effects on working times and CO_2 emissions are determined. The effects of expected trends in production and consumption on various issues (yearly growth and changes in outlet types) in relation to hub locations are also indicated.

The analyses have shown that logistics orchestration in the form of the establishment of a hub network and consolidation can lead to a reduction in logistics costs of up to 28% in the potted plant sector, but to achieve this a substantial part of the European flows is needed to be included. More specifically, to answer the following research questions:

- What LOSs are valuable for the European potted plant sector with respect to People Planet Profit issues?
  Opening hubs spread over Europe decreases logistics costs by 19% (Profit), distribution time including work shift durations by 27% (People) and kilometres hence CO_2 emissions by 9% (Planet). If the flows to, between and from these hubs are also consolidated, costs, time and CO_2 emissions decrease a further 9%, 11% and 11%, respectively. For this, consolidation of distribution flows is especially beneficial.
- What recommendations can be proposed regarding the design and implementation of LOSs for the Dutch potted plant SCN?
  A robust and gradual development path for opening hub locations can be obtained. This development path is first aimed at covering the centre of Europe and then the south and east. Depending on the future trends in supply and demand volumes in south and east Europe, the importance of hubs in the south and east may grow compared to hubs in the centre of Europe.

As the main objective of this analysis was to provide a good indication of the differences between the LOSs, an indication of absolute numbers has not been provided. Aggregate (regional) data was used and scaled down to provide useful data for scenario analysis at a supply chain level. As a result, the model has a high level of aggregation and produces estimates of cost savings rather than very precise values.

Without the optimisation model logistics orchestration would remain a purely theoretical concept. The results of the model are valuable for the corporate and governmental Dutch decision-makers in order to maintain the Dutch position in the potted plant sector in the future. The results of the model have instilled a sense of opportunity into the project partners, who have noted the relative large amount of locally produced and locally consumed products and the increasing demand for high responsiveness as the main drivers for change. The incorporation into the analysis of factors such as congestion and of emerging producing regions has also demonstrated to the project partners the urgency of effective repositioning of the Dutch potted plant sector.

Appendix A: Logistics costs calculation

Collection costs

Parameters used:

t	supplier type ($t = 1, 2, \ldots, T$)
$truckspace_p$	factor to convert volume to necessary truck space for product type p
$fraction_{st}$	fraction of supplier type t in supplier region s
$truckcap_t^s$	truck capacity for supplier type t in supplier regions
$truckload_t^s$	truck load factor of supplier type t in supplier regions
$triplength_{st}$	length of a trip in supplier region s for supplier type t (km)
$kmcost_t^s$	cost per km for supplier type t in supplier regions (€/km)
$pickups_t^s$	number of pick-ups at supplier type t in supplier regions
$pickupcost_t^s$	costs of a pick up at supplier type t in supplier regions (€)

$$
\begin{aligned}
c^s &= \text{costs to collect all products from all suppliers in all supplier regions} \\
&= \sum_s \sum_t \frac{\left[\sum_p \frac{S_{sp} - \sum_c X_{scp}^{dd} - \sum_c X_{scp}^{ll}}{truckspace_t^s}\right] fraction_{st}}{truckcap_t^s \; truckload_t^s} \times \\
&\quad (triplength_{st} \; kmcost_t^s + pickups_t^s \; pickupcost_t^s)
\end{aligned}
$$

Distribution costs

Parameters used:

u	customer type ($u = 1, 2, \ldots, U$)
$truckspace_p$	factor to convert volume to necessary truck space for product type p
$fraction_{cu}$	fraction of customer type u in customer region c
$truckcap_u^c$	truck capacity for customer type u in customer regions
$truckload_u^c$	truck load factor of customer type u in customer regions
$triplength_{cu}$	length of a trip in customer region c for customer type u (km)
$kmcost_u^c$	cost per km for customer type u in customer regions (€/km)
$drops_u^c$	number of drops at customer type u in customer regions
$dropcost_u^c$	costs of a drop at customer type u in customer regions (€)
$chainlength_u^c$	number of chain links (not including the links up to the hub(s)) for customer type u in customer regions
$crossdockcost^c$	costs per truck for crossdocking in customer regions (€)

$$
\begin{aligned}
c^c &= \text{costs to distribute all products to all customers in all customer regions} \\
&= \sum_c \sum_u \frac{\left[\sum_p \frac{D_{cp} - \sum_s X_{scp}^{dd} - \sum_s X_{scp}^{ll}}{truckspace_u^c}\right] fraction_{cu}}{truckcap_u^c \; truckload_u^c} \times \\
&\quad (triplength_{cu} \; kmcost_u^c + drops_u^c \; dropcost_u^c + chainlength_u^c \; crossdockcost^c)
\end{aligned}
$$

Transport costs from suppliers to hubs to customers

The costs calculated here are applied for transport from supplier regions to hubs, between hubs and from hubs to customer regions. In the notation a region can therefore be a supplier region, a hub location or a customer region.

Parameters used:

$return$	return logistics factor
$time_{ij}$	transport duration between region i and region j (hour)
$regioncongest_i$	additional time needed due to congestion in region i (hour)
$regioncongest_j$	additional time needed due to congestion in region j (hour)
$truckcap^{ij}$	truck capacity between regions i and j
$truckload^{ij}$	truck load factor between regions i and j
$hourcost^{ij}$	cost per hour to use a truck between regions i and j (€/hour)

$$\begin{aligned} c_{ijp} &= \text{costs to transport product type p from region i to region j} \\ &= \frac{return(time_{ij}+regioncongest_i+regioncongest_j)hourcost^{ij}}{truckcap^{ij}\ truckload^{ij}\ truckspace_p} \end{aligned}$$

Chapter 4

Hybrid optimisation and simulation to design a logistics network for distributing perishable products

De Keizer, M., Haijema, R., Bloemhof, J.M., & Van der Vorst, J.G.A.J. (2015). Hybrid optimisation and simulation to design a logistics network for distributing perishable products. *Computers & Industrial Engineering, 88*, 26–38. doi:10.1016/j.cie.2015.06.017

Abstract

Dynamics in product quality complicate the design of logistics networks for perishable products, like flowers and other agricultural products. Complications especially arise when multiple products from different origins have to come together for processes like bundling. This chapter presents a new MILP model and a hybrid optimisation-simulation (HOS) approach to identify a cost-optimal network design (i.e. facility location with flow and process allocation) under product quality requirements. The MILP model includes constraints on approximated product quality. A discrete event simulation checks the feasibility of the design that results from the MILP assuming uncertainties in supply, processing and transport. Feedback on product quality from the simulation is used to iteratively update the product quality constraints in the MILP. The HOS approach combines the strengths of strategic optimisation via MILP and operational product quality evaluation via simulation. Results, for various network structures and varying degrees of dynamics and uncertainty, show that if quality decay is not taken into account in the optimisation, low quality products are delivered to the final customer, which results in not meeting service levels and excess waste. Furthermore, case results show the effectiveness of the HOS approach, especially when the change from one iteration to the next is in the choice of locations rather than in the number of locations. It is shown that the convergence of the HOS approach depends on the gap between the product quality requirements and the quality that can be delivered according to the simulation.

4.1 Introduction

In making strategic decisions, like logistics network design or network configuration, one should take into account its tactical and operational consequences. This holds especially for designing a distribution network for perishable products, like flowers. Product quality of perishable products decays with time and this decay is accelerated if environmental conditions during distribution, most notably temperatures, are not optimal. A cost-optimal design that ignores product quality decay may result in waste and products delivered with too low quality at the final customer.

Triggered by its current trends, the cut flower sector is selected as an example to define the logistics network design problem with product quality requirements and to set the scope. The Dutch auctions are the biggest flower auctions in the world and central points in European floricultural logistics (De Keizer et al., 2012). Traders, logistics service providers, and other companies that perform value-adding activities (e.g. bouquet-making, packaging, labelling) settled near the auction locations which led to the development of floricultural clusters. As business is conducted more and more via digital channels, like virtual auctions and web shops, products do not physically have to pass the Dutch auctions or floricultural clusters anymore, which gives opportunities to reconfigure the logistics network. Strategic choices to be made are where to locate floricultural clusters (hubs) and in particular which value-adding activities (processes) to allocate to which clusters. In addition, growers (suppliers) and retailers (customers) are to be allocated to clusters.

This chapter studies the hub location problem with flow and process allocation for a perishable product logistics network, which makes that product quality decay should be taken into account. Incorporating product quality decay complicates the problem: (1) next to bouquets consisting of a single flower type, customers also demand bouquets consisting of a mix of flower types from different suppliers, which influences the flow of products and timing of processes as all flower types should be available for a process to start; (2) large transport distances and possible delays in processes due to delayed delivery of input products cause uncertainty in process and transport duration, which together with fluctuations in temperature influences product quality. Hub location problems are generally solved by optimisation models, in which constraints on product quality are at best dealt with at an aggregate or approximate level. To prevent excessive quality decay, penalty or loss costs are added to the objective function (e.g. Di et al., 2011), or time constraints are included (e.g. Zhang et al., 2003). The dynamic and stochastic nature of product quality decay can be incorporated more accurately at a detailed level in simulation models (e.g. Rijpkema et al., 2014). To combine the strengths of strategic optimisation and detailed evaluation (Figueira & Almada-Lobo, 2014), we present a hybrid optimisation and simulation (HOS) approach for designing and configuring distribution networks for fresh products, such as fresh cut flowers.

The optimisation model within our HOS approach is an MILP that is similar to Hammami & Frein (2013) in the way operational aspects are included, but we extend it to the case of multiple customers and multiple products. Furthermore, whereas Hammami & Frein (2013) focus on lead time constraints, we include product quality decay as a function of time and temperature, which causes different trade-offs in decisions. The HOS approach itself is in line with Safaei et al. (2010); Acar et al. (2009); Almeder et al. (2009); Ko et al. (2006), but differs as these papers do not deal with product quality. Moreover, whereas they use simulation outcomes for critical points within the supply chain network to steer the optimisation, we use simulation outcomes for service levels at the end of the supply chain network, which causes a different steering. Our approach altogether contributes to literature on design of logistics networks for distributing multiple perishable products due to more detailed approximations of product quality and the inclusion of dynamics and uncertainty in product quality decay. A more detailed explanation of related studies follows in the next section.

The remainder of this chapter is organised as follows. Relevant literature on network design and hybrid approaches is discussed in Section 4.2. The cut flower supply chain network together with the derived decision problem are described in Section 4.3. Next, in Section 4.4, an MILP model is formulated which incorporates product quality decay. The HOS approach which adds simulation feedback to this optimisation model is presented in Section 4.5. Results and acquired insights are discussed in Section 4.6. Section 4.7 concludes the chapter.

4.2 Literature review

In this literature section the network design problem is first positioned by discussing literature on network design specifically directed to process allocation and product quality decay. This shows that research on network design does incorporate product quality decay, but does not incorporate it's stochastic and dynamic aspects. Second, the solution approach is positioned by discussing literature on solution approaches that can incorporate stochastic and dynamic aspects in strategic decision problems, i.e. hybrid optimisation and simulation.

4.2.1 Network design, process allocation and product quality decay

The main decisions in a network design problem are generally facility location and goods flow allocation. In this chapter, the network design problem is extended with process allocation decisions. Hammami & Frein (2013) address a similar problem, they determine supplier and distribution locations as well as manufacturing locations in a global supply chain. The selected locations have an influence on the delivery lead time, and because delivery lead times should not exceed what is promised to customers, they impose restrictions on delivery lead times in their model. They formulate an MILP model in which a balance is found between capturing the impacts of lead time constraints on strategic design decisions while keeping a low level of detail of the operational aspects of lead time. Caro et al. (2012) also look at process allocation, in a food processing industry setting. They determine at which production locations to open processes (e.g. refining, extraction, separation), which products to produce with the processes and which markets to supply from which processes. Characteristic for the food processing industry is an uncertain production yield, which they incorporate by adding to the objective function penalty costs due to unmet demand that results from uncertain production yields. As a result of process allocation decisions, issues around lead time and uncertain product quantities are considered in strategic decision models, but they do not cover issues around product quality.

Taking into account product quality decay in supply chain management problems is mostly dealt with on a tactical or operational level (e.g. Rijgersberg et al., 2010; Rijpkema et al., 2014). This is due to the dynamic nature of product quality decay, which can be incorporated more accurately and detailed on a small time scale. Strategic problems can include anticipated product quality decay at an aggregate level by using deterioration or decay loss costs (Di et al., 2011; Yang et al., 2010; Gong et al., 2007; Tang et al., 2007), or by using (time) constraints (Zhang et al., 2003). Di et al. (2011) look at a facility location problem, where Yang et al. (2010); Gong et al. (2007); Tang et al. (2007) integrate this with inventory decisions. They calculate penalty or revised inventory costs that emerge because products deteriorate at a certain rate, e.g Gong et al. (2007) assume a rate which increases with distance, Yang et al. (2010); Tang et al. (2007) assume an exponential rate during transport and Di et al. (2011); Gong et al. (2007) assume an exponential rate during storage. Zhang et al. (2003) also take into account quality degradation as a penalty cost in a facility location problem, but because they search for a solution with zero penalty, they actually take into account quality degradation as a constraint. More importantly, they determine quality degradation more accurately by using a quality change model, i.e. a mathematical formulation for quality decay, which is in this case a chemical reaction kinetics function.

In summary, operational aspects of lead time requirements and uncertainty in product quantities are taken into account in research on strategic decision problems. However, there is no research that takes into account the interaction between strategic decisions and the uncertainty and dynamics of product quality at an operational level. This is therefore our contribution: we incorporate a quality decay model in an MILP at a more detailed level than has been done so far; we refine the dynamics of product quality decay at an operational level by a Discrete Event Simulation (DES) that is integrated with the MILP. In the next section, research that combines optimisation and simulation is discussed.

4.2.2 Optimisation and simulation

Combining mathematical optimisation and simulation into one solution procedure is denoted as hybrid simulation/analytic modelling (Shanthikumar & Sargent, 1983). There are multiple ways to combine the two techniques and Figueira & Almada-Lobo (2014) give an overview of categorisations along different dimensions. One technique can be used as part of the other technique, e.g. local optimisations are used to set parameters of a simulation model (Pirard et al., 2011) or a simulation model is used in a search procedure (Melouk et al., 2013; Halim & Seck, 2011; Ding et al., 2009). Also, the techniques can be used in a sequential or iterative procedure, e.g. using simulation as feedback for re-optimisation (Sel & Bilgen, 2014; Bilgen & Çelebi, 2013; Safaei et al., 2010; Acar et al., 2009; Almeder et al., 2009; Ko et al., 2006). Almeder et al. (2009) show empirically, for stochastic supply chain problems, that an iterative combination of simulation and LP performs better than just deterministic MIP models. The connection between their MILP and DES is captured in cost parameters, delay parameters and flow amounts. Ko et al. (2006) use simulation feedback to update the capacity constraints in their MIP. They determine locations of warehouses and flows of products from plants to warehouses to customers over time using a genetic algorithm. The best solution found is subsequently evaluated on average service times at the warehouses in a DES. Then, the feedback works two ways: too high service times lead to more strict capacity constraints in the MIP, too low service times lead to less strict constraints. Acar et al. (2009) give a generalised procedure for simulation feedback for optimisation under uncertainty. They develop a general MILP formulation, for which firstly a deterministic solution is determined. Secondly, simulation is used to determine the objective function value when the deterministic solution is exposed to stochastic factors. Thirdly, the difference between the deterministic and stochastic objective values is used to update the MILP formulation. Safaei et al. (2010) look at a production-distribution problem. They formulate an MILP with a total cost objective and a DES that incorporates characteristics of the production-distribution system, like breakdowns and delays, which are difficult to incorporate in the MILP. The mathematical model generates a production-distribution plan, for which realistic operation times are determined by the simulation. These operations times are subsequently used in the mathematical model, which generates a new production-distribution plan. The iterative procedure stops when the operation times from two consecutive simulation runs are close enough. The authors show that the efficiency and quality of the solution procedure depends on the stochastic characteristics (probability density functions of failure and repair times). Bilgen & Çelebi (2013) and Sel & Bilgen (2014) address a similar production-distribution problem in a network for perishable dairy products.

In summary, optimisation for parameter setting in a simulation and using simulation in a search procedure are suitable when it gets very complex to include all decisions in one analytical model. Using simulation as feedback for re-optimisation is suitable when the decision problem itself can be properly defined, but stochastic and/or dynamic factors are not incorporated accurately. Our research falls within this last class of hybrid approaches and we contribute to this with a hybrid approach concerning product quality decay. With this approach we show a different way to steer the optimisation using feedback from a DES. Furthermore, we show the added value of more detailed quality deterioration information in network design optimisation.

4.3 Network description

The cut flower sector is used as an example to define the strategic decision problem and to set the scope. Therefore, a common cut flower supply chain is first described. Subsequently, this is translated into a supply chain model that can be used for the HOS approach .

Figure 4.1 shows a cut flower supply chain network from growers to retail outlets via floricultural trading clusters consisting of auctions and traders. Growers supply their products to an auction. The auction uses a given schedule for auctioning, which means that growers must have their cut flowers delivered to the auction location at given times. Traders, also part of the floricultural cluster, are then bidding on the products at the auction. When a trader has acquired a batch of cut flowers the products have to be delivered to the trader location within a given time. Next, the trader processes flowers to produce bouquets, after which the bouquets are distributed to the retailers. Retailers provide times at which they want to be delivered, which results in cut-off times for processes (e.g. to have products ready for transport at 16 o'clock, processing starts at 12 o'clock). At given times scrap products (e.g. cut flowers offered but not sold at the auction, or cut flowers waiting to be processed for too long) are disposed as these products will no longer be able to meet the product quality requirements. Traders can also directly purchase cut flowers from growers instead of via the auction. This shortens the supply chain, but the logic of delivery and cut-off times stays the same.

Critical when redesigning a cut flower supply chain network is the allocation of bouquet-making processes. Bouquets take more volume in transport than the flowers in it, which would argue for producing the bouquets close to the retailers. However, centralisation of bouquet-making is beneficial to gain economies of scale in processing. Furthermore, as different flows with cut flowers have to come together to be able to compose a bouquet, moving the bouquet-making process further away from growers increases the risk of poor timing of the different flower flows and with that the risk of

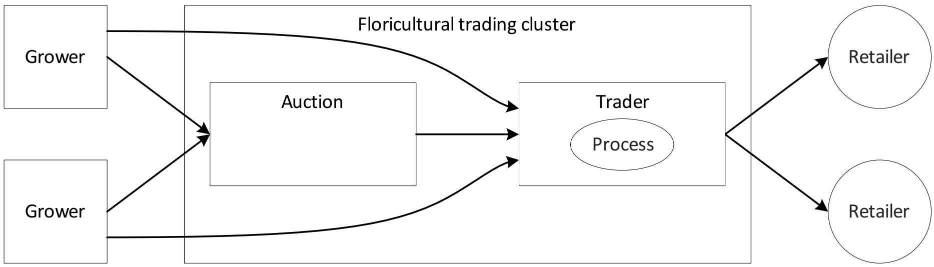


Figure 4.1: Structure of the cut flower retail supply chain network

poor product quality. Hence, allocation of the bouquet-making process is key in the trade-off between costs and product quality in the logistics network design problem.

Figure 4.2 shows a schematic representation of the model of the cut flower retail supply chain network. This model is a generalisation of Figure 4.1 and defines the scope of the problem. Floricultural clusters in between growers and retailers are denoted as hubs. At these hubs bouquet-making processes can be executed. A buffer is included to represent the time needed at hubs between transport and processes (e.g. (un)loading, auctioning, order-picking). Flows in the network are either flowers or bouquets and are represented by two types of arcs to distinguish transport flows between locations from product flows within a hub.

The auction as main trading system balances supply and demand. Therefore, it is assumed that the growers supply what is demanded by the retailers. The flow of products through the network starts with transporting the supply of growers from grower locations to hub locations. At the hub locations it is put into a buffer. Next, the products can either be transported internally to a process or be transported externally to another hub location or to a retailer location. If processed internally, the products are sent back to the buffer after finishing the process.

Product quality of cut flowers is expressed as vase life (VL), which Tromp et al. (2012) define as "the time (in days) that flowers can be kept on the vase at room temperature, which is regularly assumed to be equal to 20^oC". Quality degradation is determined using a quality change model denoted as the degree-days model (Tromp et al., 2012). This model is based on the vase life of cut flowers at the beginning of the logistics chain (A) and the Time Temperature Sum (TTS): $VL = A - \frac{1}{20}TTS$. TTS is calculated from times (in days) and temperatures throughout the logistics chain: $TTS = \sum_i time_i * temperature_i$ where i is a process in the logistics chain during which temperature is approximately constant. Each retailer is assumed to require a certain service level, i.e. a percentage of all products delivered at his location to have a vase life that at least meets a certain minimum level. All in all, a design of the network should be found, i.e. hub locations, and process and flow allocations, that minimises costs while meeting product quality requirements.

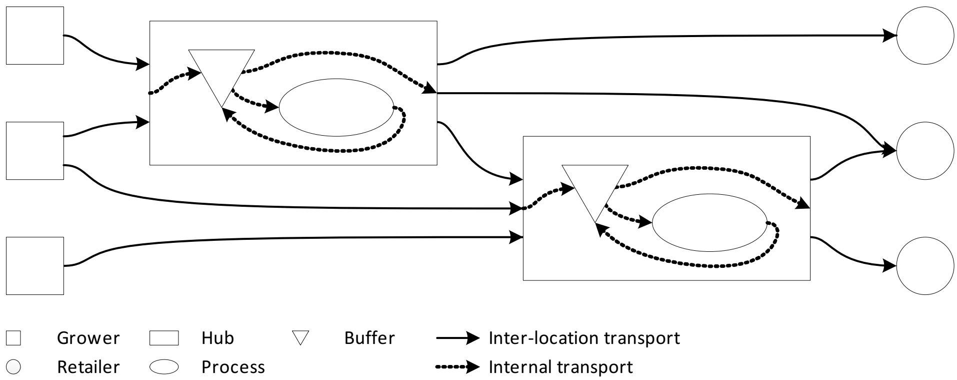


Figure 4.2: A schematic representation of a generalised cut flower supply chain network model

4.4 Optimisation with product quality constraints

A multi-product MILP for logistics network design, i.e. facility location and process and flow allocation, is defined. A given supply for growers and a given demand for retailers is assumed such that the quantities comply with supply just meeting demand. Subsequently, product quality is incorporated by defining a constraint that uses TTSs of transport links, processes and hub buffers. Quality of a product delivered to a retailer is determined by the degree days model (Tromp et al., 2012) in which total TTS of a logistics flow through a supply chain is a variable. Product quality decay is thus associated with a path through the network, which would argue for a path-based formulation of the logistics network design problem. However, a path-based formulation can easily lead to an explosion of the number of variables in the MILP and therefore the common facility location-allocation problem formulation is used which defines variables for flows between locations (Daskin et al., 2005). As detailed product flows cannot be incorporated at this level, an approximation for the total TTS is composed. First, the basic network design problem without considering product quality and TTS is formulated, referred to as MILP−. Then, a reasoning similar to Hammami & Frein (2013) is used to extend the basic problem with TTS constraints for product quality control, referred to as MILP+.

4.4.1 MILP−: Basic model without product quality constraints

Indices and sets:

$g \in G$	set of growers
$r \in R$	set of retailers
$i, j \in H$	set of hubs
$p, q \in P$	set of products (both flowers and bouquets)

Decision variables:

$Y_i \in \{0,1\}$	hub i open or not
$Y_{ip} \in \{0,1\}$	process producing product p installed at hub i or not (1 if $X_{ip} > 0$, 0 otherwise)
$XG_{gip} \geq 0$	quantity of product p transported from grower g to hub i
$XH_{ijp} \geq 0$	quantity of product p transported from hub i to hub j
$XR_{irp} \geq 0$	quantity of product p transported from hub i to retailer r
$X_{ip} \geq 0$	quantity of product p produced at hub i

Parameters:

fc_i	fixed costs for opening hub i
fc_{ip}	fixed costs for installing the process producing product p at hub i
cg_{gip}	unit transportation costs of product p from grower g to hub i
ch_{ijp}	unit transportation costs of product p from hub i to hub j
cr_{irp}	unit transportation costs of product p from hub i to retailer r
c_{ip}	unit production costs of product p at hub i
sup_{gp}	supply of product p by grower g
dem_{rp}	demand of product p by retailer r
m_{pq}	quantity of product p in one unit of product q

$$\begin{aligned} \min \quad & \sum_{i\in H} fc_i Y_i + \sum_{i\in H}\sum_{p\in P} fc_{ip} Y_{ip} + \sum_{g\in G}\sum_{i\in H}\sum_{p\in P} cg_{gip} XG_{gip} \\ & + \sum_{i\in H}\sum_{j\in H}\sum_{p\in P} ch_{ijp} XH_{ijp} + \sum_{i\in H}\sum_{r\in R}\sum_{p\in P} cr_{irp} XR_{irp} + \sum_{i\in H}\sum_{p\in P} c_{ip} X_{ip} \end{aligned} \tag{4.1}$$

$$s.t. \quad \sum_{i\in H} XG_{gip} = sup_{gp} \qquad \forall g \in G, p \in P \tag{4.2}$$

$$\sum_{i\in H} XR_{irp} = dem_{rp} \qquad \forall r \in R, p \in P \tag{4.3}$$

$$\sum_{g\in G} XG_{gip} + \sum_{j\in H} XH_{jip} + X_{ip} = \sum_{j\in H} XH_{ijp} + \sum_{r\in R} XR_{irp} + \sum_{q\in P} m_{pq} X_{iq} \qquad \forall i \in H, p \in P \tag{4.4}$$

$$\sum_{g\in G}\sum_{p\in P} XG_{gip} + \sum_{j\in H}\sum_{p\in P} XH_{jip} + \sum_{p\in P} X_{ip} \leq \left[\sum_{g\in G}\sum_{p\in P} sup_{gp}\right] Y_i \qquad \forall i \in H \tag{4.5}$$

$$X_{ip} \leq \left[\max_{p\in P} \sum_{g\in G} sup_{gp}\right] Y_{ip} \qquad \forall i \in H, p \in P \tag{4.6}$$

The objective (4.1) is to minimise fixed location and process costs, transportation costs for links from growers to hubs, between hubs and from hubs to retailers, and variable process costs. Equation (4.2) and (4.3) give supply and demand balance constraints. Hub balance constraints are given in Equation (4.4). Product inflow of a hub are products supplied by a grower or another hub, and products produced by a process at the hub. Product outflow of a hub are products send to another hub or a retailer, and products further processed at the hub (product inflows of a process are multiples of product outflow of a process). Equation (4.5) and (4.6) ensure that flows into a hub can only be allocated if the hub is open, and that flow out of a process can only exist if the process is installed.

4.4.2 MILP+: Extended model with Time Temperature Sum constraints

In order to put a constraint on the total TTS from grower via hubs to retailer, TTS is approximated via backward reasoning similar to Hammami & Frein (2013). In this chapter, their model is extended to the multiple customers and multiple products case, which increases the complexity. Hammami & Frein (2013) introduce a representative order to calculate the lead time for which they define extra flow decision variables. This is simplified by using already defined flow decision variables.

Sets:

P_p set of input products for process that produces product p

Auxiliary variables:

$\widetilde{YG}_{gip} \in \{0,1\}$ equals 1 if $XG_{gip} > 0$, 0 otherwise
$\widetilde{YH}_{ijp} \in \{0,1\}$ equals 1 if $XH_{ijp} > 0$, 0 otherwise
$\widetilde{YR}_{irp} \in \{0,1\}$ equals 1 if $XR_{irp} > 0$, 0 otherwise
$\widetilde{TTSR}_{rp} \geq 0$ maximum TTS for getting product p to retailer r
$\widetilde{TTSH}_{ip} \geq 0$ maximum TTS for getting product p to hub i

Parameters:

$ttsg_{gip}$ TTS for transportation of product p from grower g to hub i (e.g. transport takes 4 hours, temperature during transport is 8^oC, then $ttsg_{gip} = 4/24 \cdot 8 = 2.5$ degree-days)
$ttsh_{ijp}$ TTS for transportation of product p from hub i to hub j
$ttsr_{irp}$ TTS for transportation of product p from hub i to retailer r
tts_{ip} TTS for production of product p at hub i
$ttsb_{ip}$ TTS for buffer of product p at hub i

$maxtts_{rp}$	maximum TTS to have good quality of product p for retailer r
up_{ip}	upperbound on $\widetilde{TTSH}_{ip}$

Products are delivered to a retailer from a hub. Therefore, the TTS to get product p to retailer r is the sum of the TTS to get product p to hub i and the TTS for transportation of product p from hub i to retailer r:

$$\widetilde{TTSR}_{rp} = \max_{i \in H} \left\{ \left(\widetilde{TTSH}_{ip} + ttsr_{irp} \right) \widetilde{YR}_{irp} \right\} \tag{4.7}$$

Subsequently, the TTS to get product p to hub i consists of three parts as there are three ways to get product p to hub i:

1. When product p is acquired from grower g, the TTS up to hub i is equal to the TTS for transportation of product p from grower g to hub i plus the TTS to buffer product p at hub i:

   $$\widetilde{TTSH}_{ip}^{grower} = \max_{g \in G} \left\{ (ttsg_{gip} + ttsb_{ip}) \widetilde{YG}_{gip} \right\}$$

2. When product p is acquired from another hub j, the TTS up to hub i is composed of the TTS to get product p to hub j, the TTS for transportation of product p from hub j to hub i and the TTS to buffer product p at hub i:

   $$\widetilde{TTSH}_{ip}^{hub} = \max_{j \in H} \left\{ \left(\widetilde{TTSH}_{jp} + ttsh_{jip} + ttsb_{ip} \right) \widetilde{YH}_{jip} \right\}$$

3. When product p is acquired from a process, the TTS up to hub i is composed of the TTS to get input product q to hub i, the TTS to produce product p at hub i and the TTS to buffer product p at hub i:

   $$\widetilde{TTSH}_{ip}^{process} = \max_{q \in P_p} \left\{ \left(\widetilde{TTSH}_{iq} + tts_{ip} + ttsb_{ip} \right) Y_{ip} \right\}$$

$$\widetilde{TTSH}_{ip} = \max \left[\widetilde{TTSH}_{ip}^{grower}, \widetilde{TTSH}_{ip}^{hub}, \widetilde{TTSH}_{ip}^{process} \right] \tag{4.8}$$

In the end, $\widetilde{TTSR}_{rp}$ is required to be smaller or equal to $maxtts_{rp}$ for each retailer r and product p. Therefore, together with eliminating the maximum operators from (4.7) and (4.8), the following constraints are added to the basic formulation:

$$\left(\widetilde{TTSH}_{ip} + ttsr_{irp} \right) \widetilde{YR}_{irp} \leq maxtts_{rp} \qquad \forall i \in H, r \in R, p \in P \tag{4.9}$$

$$(ttsg_{gip} + ttsb_{ip}) \widetilde{YG}_{gip} \leq \widetilde{TTSH}_{ip} \qquad \forall g \in G, i \in H, p \in P \tag{4.10}$$

$$\left(\widetilde{TTSH}_{jp} + ttsh_{jip} + ttsb_{ip}\right)\widetilde{YH}_{jip} \leq \widetilde{TTSH}_{ip} \qquad \forall i, j \in H, p \in P \quad (4.11)$$

$$\left(\widetilde{TTSH}_{iq} + tts_{ip} + ttsb_{ip}\right) Y_{ip} \leq \widetilde{TTSH}_{ip} \qquad \forall i \in H, p \in P, q \in P \quad (4.12)$$

Constraints (4.9), (4.11) and (4.12) are non-linear as they contain products of binary and bounded non-negative variables. In the appendix, it is explained how these constraints can be transformed into sets of linear constraints (Equation 4.13a) to (4.13d), (4.14a) to (4.14d) and (4.15a) to (4.15d)). The final model formulation then consists of (4.1) to (4.6), extended with (4.10), (4.13a) to (4.15d).

Note: The model will have some redundant constraints, because not every product in P is an input for or an output of a process. Based on process descriptions, these constraints are removed from the model before solving.

4.5 Hybrid optimisation and simulation approach

An optimisation and simulation approach, referred to as HOS, is developed for which the structure is depicted in Figure 4.3 (similar to Safaei et al., 2010).

1. The starting point is a network design module that solves MILP+ as formulated in Section 4.4. Output is a network design which indicates the selected hubs (Y_i), allocated processes (Y_{ip}) and product flows (XG_{gip}, XH_{ijp}, XR_{irp}, X_{ip}).
2. The design is passed to a network evaluation module, which is the DES as formulated in Section 4.5.1. Output are achieved service levels per retailer and product (γ_{rp}).
3. Information gathered with the evaluation module is fed back to the network design module until a stopping criterion is reached, as discussed in Section 4.5.2. Step 1 and 2 form one iteration. Iterations are stopped if all product quality service levels for all retailers are met in step 2 or if a given number of iterations is conducted.

Next, the DES model is described. Subsequently, the interaction between MILP+ and the DES is explained.

4.5.1 Simulation model

Using the framework of Robinson (2007), the DES model is described in three parts: objective and scope, level of detail and data requirements.

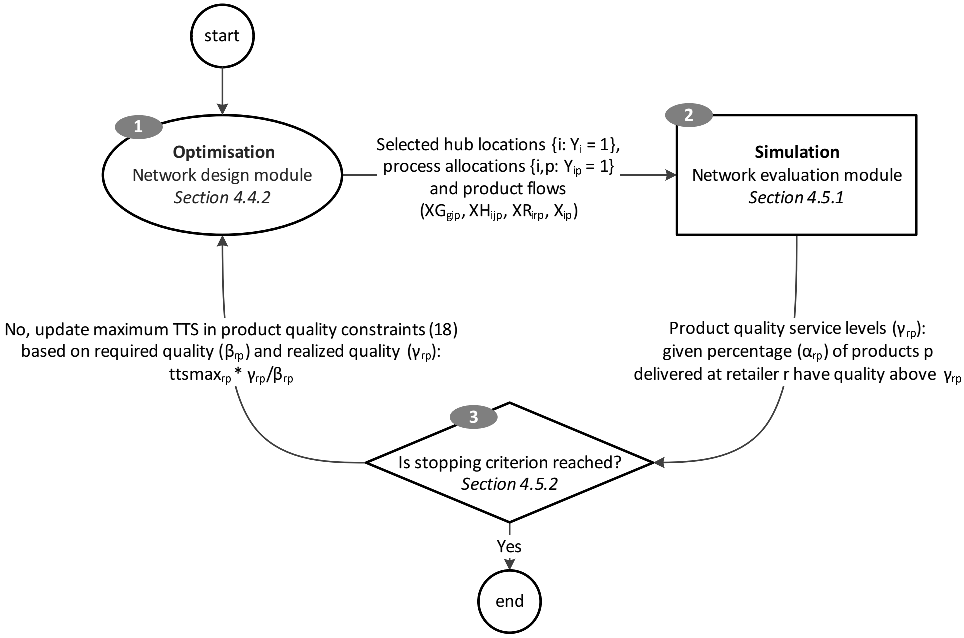


Figure 4.3: Optimisation and simulation approach

Objective and scope

In MILP+ product quality requirements are modelled approximately by TTS constraints. The main objective for the network design simulation is to check whether service levels for product quality requirements are met, and to specify how the TTS constraints in MILP+ can be adjusted to get a feasible or improved solution. The scope is similar to MILP+: the flow of products through the cut flower supply chain network is modelled from the loading area of growers till product delivery at retailers. The scope thus includes transport and buffering and processing at hubs. To accurately measure product quality decay, the simulation model is a discrete event simulation model that simulates, for a given network design, fluctuations in supply quality and quantity, temperature and transport and processing times. The DES model accepts as main experimental factor a network design. Output of the DES model is the percentage of delivered bouquets that has satisfactory product quality.

Each run of the simulation model starts with an empty system. The time horizon of each run is set to a given number of days of which a first couple of days is used as warmup period. The finite length of the simulation is a logical choice given that processing the supply of successive days is not intertwined due to daily disposal of scrap products. By executing multiple runs the performance of a network design in meeting the constraints on product quality can be estimated.

Level of detail

Flow items or **entities** in the simulation are either a bundle of flowers or a bundle of bouquets, where a bundle denotes an aggregation of 500 products. Modelling individual flowers or bouquets would make the DES too slow and would not lead to a more accurate model to predict the service level at retailers with respect to product quality.

Activities in the simulation are growers (sources), retailers (sinks) and bouquet-making processes. Each grower is a component that creates a batch of entities per flower type each day. The sizes of these batches are drawn from a normal distribution. Each retailer is a component that receives bundles of bouquets. Each process is a component that receives bundles of flowers and holds the entities within a items list until a given cut-off time. At this cut-off time the bundles of flowers that are available in the items list are turned into bundles of bouquets according to given proportions (i.e. it is given how much bundles are needed of each flower type to produce one bundle of bouquets). If the quantities of available entities are not an exact multiple of the proportions in a bouquet, leftover entities are kept in the items list until the next cut-off time. This makes the batch size of a process dependent on the quantities of available bundles of flowers. The process time of a batch is a time slot and is drawn from a normal distribution at the cut-off time. At the end of each day entities that are still waiting to be processed are examined and if they have been waiting for too long (i.e. it is given per flower type how long they are allowed to be waiting which is related to the degree of perishability of the flower type) they are discarded.

FIFO-**queues** or buffers are incorporated to handle incoming flows of bundles, which are temporarily stored before they go into a bouquet-making process or are transported to another location. Buffers are modelled with gated control to represent WIP inventory in the supply chain: when the capacity of the buffer is reached, or when entities have been in the buffer for a given fixed duration, the entities are released.

Resources in the simulation are transporters, which represent trucks that transport one type of product between locations. A transporter has a loading time at its origin and then travels with a given speed to its destination. Uncertainty in the arrival of trucks, the availability of loading and unloading docks and the time needed for loading and unloading is aggregated in the loading time and is drawn from a normal distribution. Transport times are fixed by distance and speed. When a transporter has reached its destination it immediately goes back to its origin and there is always a transporter available. Internal transport between a buffer and a bouquet-making process is not modelled separately as internal traveling times are relatively short (and may be included in the buffering or processing time).

The simulation tracks **quality decay** and records the actual product quality for each entity. When bundles of flowers are created the entities are randomly assigned an initial product quality which is drawn from a normal distribution. At the end of every

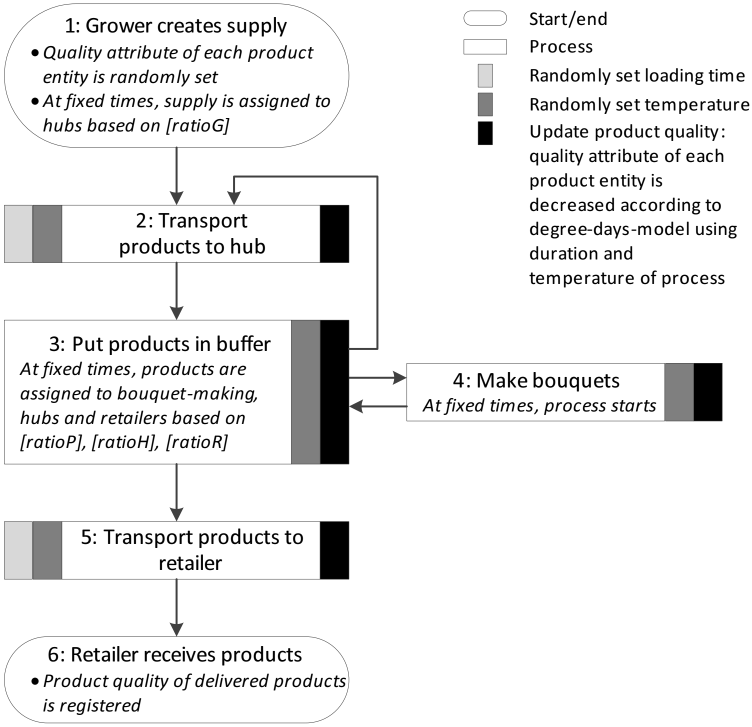


Figure 4.4: Process flow diagram of DES model

transport, or when entities leave a buffer, or when processing is finished, the product quality attribute of the entity is updated using the degree-days model with simulated durations and temperatures. When processing, the product quality of the produced entity is first determined as the minimum product quality of the used entities which is then updated using the degree-days model. All temperatures are drawn from a normal distribution at discrete points in time. For transport the temperature is set when the entities are loaded. As the temperature of bundles in a buffer are correlated but may not be identical, the temperature during buffering of a bundle is set when an entity leaves the buffer. For a bouquet-making process the temperature during processing is set at the cut-off time of the process. During transport, buffering, or processing the temperature of a bundle is assumed to remain constant.

The growers and retailers in the simulation are given, the hub buffers and processes are determined by MILP+: if binary variable Y_i is equal to 1 buffers at hub i are included in the simulation and if binary variable Y_{ip} is equal to 1 a process producing product p at hub i is included in the simulation. A **process flow** diagram of the DES model is given in Figure 4.4. At a grower bundles of flowers are created, loaded into a transporter and send to a buffer at a hub. From a buffer the bundles of flowers either go into a bouquet-making process or they are loaded into a transporter and send to a buffer at another hub. If the bundles go into a bouquet-making process, the produced bundles of bouquets are in turn put in a buffer. Bundles of bouquets then are loaded from a buffer into a transporter and send either to a buffer at another hub or to a retailer. The assignment of bundles to transporters and processes is based on fixed ratios equal to those in MILP+:

[ratioG] A batch with sb_{gp} bundles of product p is created at grower g. In MILP+, a total of $\sum_{j \in H} XG_{gjp}$ products p is supplied by grower g, of which XG_{gip} products go to hub i. Applying the same ratio, $sb_{gp} \cdot \frac{XG_{gip}}{\sum_{j \in H} XG_{gjp}}$ bundles of the batch are send to the buffer holding product p at hub i.

[ratioP] A buffer at hub i contains b_{ip} bundles of product p. In MILP+, the total number of products p that leave the buffer is $T_{ip} = \sum_{r' \in R} XR_{ir'p} + \sum_{j' \in H} XH_{ij'p} + \sum_{q' \in P} m_{pq'} X_{iq'}$. Of this total, $m_{pq} X_{iq}$ products p go into a process that produces product q. Applying the same ratio, $b_{ip} \cdot \frac{m_{pq} X_{iq}}{T_{ip}}$ of the bundles buffered are destined for the process producing product q at hub i.

[ratioH] Continuing the reasoning, XH_{ijp} products p of total T_{ip} go to hub j. Then, $b_{ip} \cdot \frac{XH_{ijp}}{T_{ip}}$ of the bundles buffered are send to hub j.

[ratioR] Finally, XR_{irp} products p of total T_{ip} go to retailer r. Thus, $b_{ip} \cdot \frac{XR_{irp}}{T_{ip}}$ of the bundles buffered are send to retailer r.

Data requirements

Each retailer requires a certain service level for a product, i.e. a percentage (α_{rp}) of products p delivered at retailer r should have a vase life above a minimum level (β_{rp}). Therefore, the output of the DES model is the service level that is actually achieved (γ_{rp}). For this, the product quality attribute, i.e. vase life, of each product p that reaches retailer r is registered. This data is turned into a vase life distribution at the end of a simulation run and the achieved service level is calculated as the (1 - α_{rp})-percentile of this distribution (examples are given in Figure 4.5). All inputs and outputs for the DES model are given in Table 4.1.

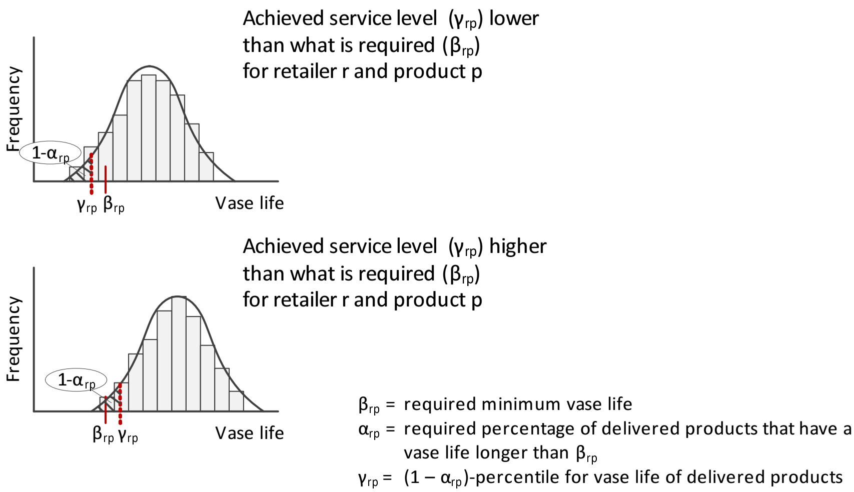


Figure 4.5: Relation between product quality percentiles and service levels

4.5.2 Interaction between optimisation and simulation

Use of the MILP for the simulation and vice versa is given in pseudo-code in Algorithm 4.1 (adjustments to product quality constraints are similar to capacity adjustments in Ko et al. (2006)). Two aspects are to be noted about the interaction between MILP+ and the DES. On the one hand, as the feedback essentially effectuates at the end of the chain, there remains flexibility for MILP+ in how to re-optimise the network. On the other hand, due to transport and processing, especially combining different flowers into bouquets, a maximum TTS value update for one product and retailer not only affects the TTS constraint for that product and retailer but also the associated TTS constraints throughout the chain and with that constraints for other products and retailers.

4.5.3 Implementation

The HOS approach is developed in C++ and FlexSim (6.0.2). A FlexSim module dll is coded in which MILP+ is solved using the ILOG CPLEX C++ framework (12.4), and in which FlexSim objects are instantiated to construct a simulation in the FlexSim environment. Iteration logic is also programmed in the dll. The model is run on a laptop with a 2.40 GHz Intel core i5 and 4GB RAM (CPLEX uses up to 100% of CPU capacity, simulations in FlexSim can run only on one thread and use up to 25% of CPU capacity). To improve runtime, the MILP solution from the last iteration is used as start in the new MILP optimisation.

Table 4.1: Inputs and outputs for simulation

Deterministic input	Stochastic input
Grower	
• Location • Destination (based on [ratioG])	• Supply batch size $\sim N(\mu_s, \sigma_s)$ • Initial product quality $\sim N(\mu_i, \sigma_i)$
Buffer at hub	
• Location (based on Y_i in MILP+) • Capacity • Maximum staytime • Destination (based on [ratioP], [ratioH], [ratioR])	• Temperature $\sim N(\mu_{tb}, \sigma_{tb})$
Bouquet making at hub	
• Location (based on Y_{ip} in MILP+) • Quantities of input products needed to produce one output product • Maximum waiting time for input products • Cut-off times	• Temperature $\sim N(\mu_{tp}, \sigma_{tp})$ • Processing time $\sim N(\mu_p, \sigma_p)$
Retailer	
• Location	
Transporter	
• Number available • Capacity • Speed	• Temperature $\sim N(\mu_{tt}, \sigma_{tt})$ • Loading time $\sim N(\mu_l, \sigma_l)$
Output: Delivered product quality percentile at retailer (γ_{rp})	

4.6 Scenarios and Results

A base scenario and eight variations on this base scenario are generated to test the HOS approach. First the scenarios are described and subsequently the results.

4.6.1 Scenarios

A base scenario is generated based on general data from the Dutch cut flower retail chain. For confidentiality reasons, locations are put on a Euclidean grid rather than showing the real network. Furthermore, three groups of scenarios are generated that deviate from the base scenario in dynamics (i.e. timing in processes), uncertainty and network structure respectively. These scenarios are used to test the HOS model and to get insight in when the simulation feedback in the HOS approach provides added value compared to models MILP− and MILP+.

As a result of virtualisation the physical auction locations in the cut flower supply chain network can be decoupled from the physical logistics locations. This allows for a greenfield approach with respect to hub locations in the scenarios. The Dutch cut flower sector mainly acts in the centre and the south of Europe, which is represented by a comparable sized grid. As cut flowers are mostly grown in or transported via the

Algorithm 4.1: Algorithm in pseudo-code

Algorithm: HOS approach

Result: Heuristically determines a network design that minimises costs and meets product quality constraints

Initialisation:

$stop = false$; $iter = 0$; $maxiter$ = maximum number of iterations; N = number of simulation runs;

$maxtts_{rp}$ = maximum TTS for retailer r and product p;
β_{rp} = service level of retailer r for product p;

ϵ = small number; $\lambda_{relax} \in (1, \infty)$; $\lambda_{restrict} \in (0, 1)$;

while *not stop* **do**
  Step 1:
  repeat
    Run MILP+;
    if *No feasible solution* **then**
      Relax product quality constraints (4.9):
      $maxtts_{rp} = \lambda_{relax} \cdot maxtts_{rp} \quad \forall$ retailer r, product p;
    end
  until *Feasible solution is found for MILP+*;

  Step 2:
  a: Configure DES model with MILP+ solution;
  b: Run DES model N times; Provides average achieved service levels γ_{rp};
  c: Use γ_{rp} to check whether delivered products meet service level:
    if $\gamma_{rp} >= \beta_{rp}(1 - \epsilon) \quad \forall$ *retailer r, product p* **then**
      Required service levels are reached;
      $stop = true$;
    else
      foreach *retailer r, product p* **do**
        if $\gamma_{rp} < \beta_{rp}(1 - \epsilon)$ **then**
          Update (4.9): $maxtts_{rp} = \gamma_{rp}/\beta_{rp} \cdot maxtts_{rp}$;
        else if γ_{rp} *not determined* **then**
          Too much of product p is wasted to meet demand of retailer r;
          Restrict (4.9): $maxtts_{rp} = \lambda_{restrict} \cdot maxtts_{rp}$;

      end
    end

  $iter = iter + 1$;
  if $iter > maxiter$ **then**
    $stop = true$;

end

Return best solution

Netherlands and the south of Europe, a grower region is created in the north-east and in the south-east of the grid. Each grower supplies one type of product out of five cut flower types and two green ornamental types. There are two processes which start twice a day. One process creates mono bouquets (a bouquet that consist of one cut flower type only) and one process creates mixed bouquets (a bouquet that consists of different cut flower types and green ornamentals). The bouquets that are produced are demanded by ten retailers. As the north of Europe (the Netherlands, Germany, etc.) is the core of the European cut flower sector and as long lead times justify use of a hub network, retailers are randomly spread over the north-east of the grid. Retailers are differentiated on product quality and service level requirements. Processes can be installed at nine potential hubs (Hammami & Frein (2013) show that MILP runtimes increase especially in the number of potential hubs, in this case nine hubs give reasonable runtimes) that are located near growers, retailers or the center of the grid. The hubs and processes are differentiated on time. Further up the chain a larger time buffer is assumed to compensate for more complexity in timing of flows. More central hubs can benefit from economies of scale and therefore time is shorter. For transport a differentiation is made on costs and temperature. Transport costs are based on time, product volume and transport type. First, when transport takes more than 6 hours, cooled transport is used which costs more than uncooled transport. Second, bouquets take up more volume than single flowers and are thus more expensive to transport. Third, transport between hubs is less expensive than transport from growers and to retailers because of consolidation (more full-load trucks). Transport temperature is divided in cooled ($7°C$) and uncooled transport ($14°C$). Uncertainty is incorporated by setting the standard deviation of uncertain parameters (Table 4.1) to 1% of their average. Total supply volume and transport costs are derived from real data. Data is summarised in Figure 4.6 and Table 4.2a to 4.2d.

The fewer moments there are on a day to start a bouquet-making process, the more difficult it will be to prevent long waiting times as a result of poorly timed transports containing input products for the process. Therefore, in the first group of scenarios the cut-off times for the processes are changed from twice a day to every hour and make everything deterministic to see the added value of the simulation when it comes to dynamics. In the second group of scenarios uncertainty is varied. The standard deviation of uncertain parameters is changed from 0 to 5% of their average. These scenarios show the added value of the simulation when it comes to uncertainty. To analyse the effect of network structure on solutions and performance of the HOS approach a third group of scenarios is generated in which retailer locations, hubs and processes, and transport are changed respectively. For the first scenario, retailer locations are spread over the north of the grid instead of only the north-east, so that grower and retailer regions are not disjunct anymore. In the second scenario, buffer times and process times at hubs are all the same, in order to investigate influence of distinctiveness of locations. In the third

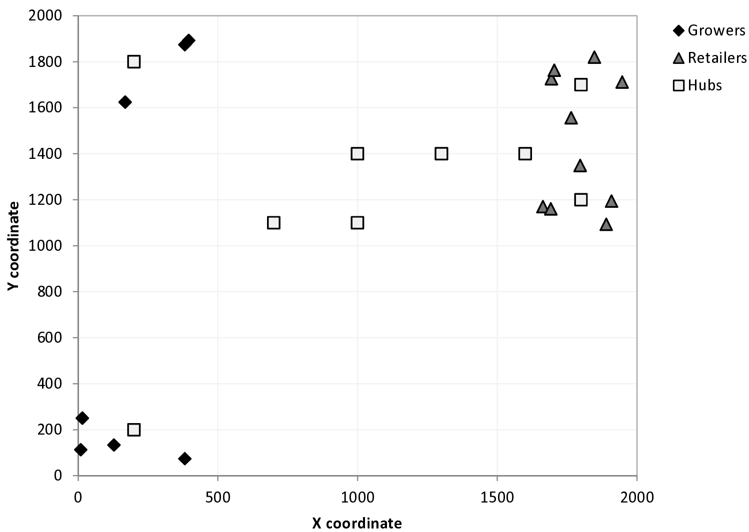


Figure 4.6: Base scenario network of growers, hubs and retailers

scenario all transport is cooled and costs are lowered to the level of uncooled transport, in order to investigate the influence of distinctiveness of transport.

To prevent excessive runtimes, a time limit of one hour is set for solving the MILP. A time horizon of 35 days with a warm-up period of 7 days is set for the simulation. Subsequently, in order to ensure that the standard deviation of γ_{rp} is at most 1% of its mean over the simulation runs in an iteration, the number of replications is set to 10. The stopping criterion for the base scenario is the fulfillment of all product quality service levels for all retailers with ϵ set to 0.01. The maximum number of iterations is set to 25 (the number of iterations needed for the base scenario plus 25%).

4.6.2 Results

In about each iteration, the runtime of the MILP reaches its limit of one hour and the runtime of the DES is around 30 minutes. Therefore, in the subsequent discussion, the number of iterations is used as indicator for the runtime of the HOS approach.

Results for the base scenario, in which processes are executed twice a day and standard deviation of uncertain parameters is 1% of their average, are summarised in Table 4.3. The network designs are shown in Figure 4.7. MILP$-$ finds a purely cost-optimal solution in which four hubs are selected, one in each grower region and one in each retailer region. However, hubs in retailer regions take up more time and therefore product quality requirements cannot be met. This is indicated by the negative value of the worst deviation of simulated service levels relative to their associated required service

Table 4.2: Input data for base scenario

(a) Product composition and supply data (initial product quality is 11 days of vase life for all products)

	Alstroemeria	Lilium	Tulipa	Gerbera	Pittosporum	Rosa	Ruscus
Mono bouquet			15				
Mixed bouquet	3	3		3	4	5	4
Supply (x1,000,000)	66	66	164	66	87	109	87
Supplied from	north-east			south-east			

(b) Retailer types

		Service level (% of delivered products with required quality)	
		90%	95%
Required product quality (days of vase life)	8	Customer 1, 3, 10	Customer 2, 4, 9
	9	Customer 6, 7	Customer 5, 8

(c) Hub and process data

Hub type	Fixed costs (x10,000)		Variable process costs	Temperature	Time (hours)		
					Hub	Process	
	Hub	Process				Handling	Cut-off
Grower region	€50	€5	€50	15°C	8	5	2x/day
Central grower region	€50	€5	€50	15°C	3	4	2x/day
Central	€50	€5	€50	15°C	5	3	2x/day
Central retailer region	€50	€5	€50	15°C	9	4	2x/day
Retailer region	€50	€5	€50	15°C	12	5	2x/day

(d) Transport types

Transport type	Temperature		Costs/km/1000 products			
			Flower		Bouquet	
	< 6 hrs	> 6 hrs	< 6 hrs	> 6 hrs	< 6 hrs	> 6 hrs
Grower to hub			€0.007	€0.011		
Hub to hub	14°C	7°C	€0.005	€0.006	€0.15	€0.17
Hub to retailer					€0.21	€0.32

levels ($\Delta_{min} = \min_r\{(\gamma_{rp} - \beta_{rp})/\beta_{rp} * 100\}$). Especially product quality requirements for mixed bouquets cannot be met because different product flows have to be combined which causes more timing issues compared to mono bouquets for which only one product flow is needed. MILP+ centralises distribution at the end of the chain. Instead of having a hub in each retailer region, a hub in between both retailer regions takes

MILP−: lowest costs, but product quality service levels not reached

MILP+: higher product quality, but service levels still not reached

HOS: service levels reached at higher costs

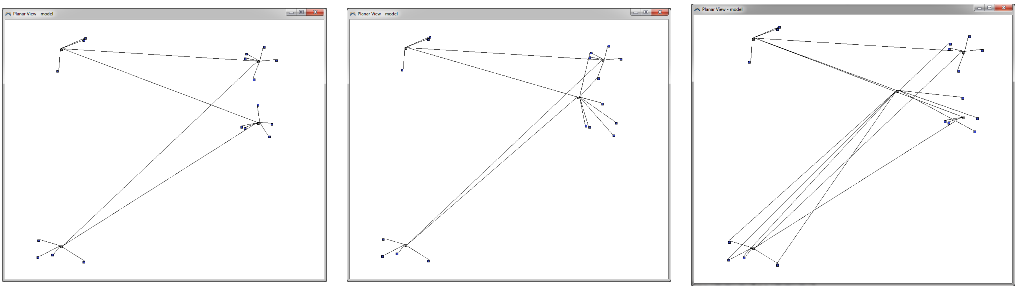


Figure 4.7: Summary of network designs for base scenario

over all processing and distribution for the south retailer hub and most processing and distribution for the north retailer hub. However, due to dynamics and uncertainties product quality requirements can still not be met. HOS centralises distribution more and more and after 20 iterations crucial constraints are tightened to the point that requirements suddenly can be met (Figure 4.8). This is indicated by a positive value of Δ_{min}. Due to long runtimes, iterations are stopped as soon as Δ_{min} is positive. With regard to runtimes, solving MILP− takes a few seconds. Solving MILP+ also takes a few seconds at first, but runtime increases abruptly (and reaches the limit of one hour) when the product quality constraints get tightened more and more in the iterations of the HOS model. Only the HOS model is able to find an operational feasible solution, but runtime increases to several hours depending on runtime of MILP+ and the simulation, and on the number of iterations needed to find the solution.

Results for the first group of scenarios, in which the cut-off times for the processes are changed from twice a day to every hour, are summarised in Table 4.4. As delivered product quality percentiles are further away from the required product quality in the first iteration(s) when cut-off times decrease, constraints are tightened more quickly and the optimal network is found with less iterations. While product quality improves more

Table 4.3: Summary of base scenario

	Costs (mln €)	$\Delta_{min} = \min_r\{(\gamma_{rp} - \beta_{rp})/\beta_{rp} * 100\}^a$ (%)	
		Mono bouquet	Mixed bouquet
MILP−	12.32	-6.90	-6.76
MILP+	13.03	-4.64	-6.19
HOS	15.51	2.39	2.84

[a] See Section 4.5.2 for notation

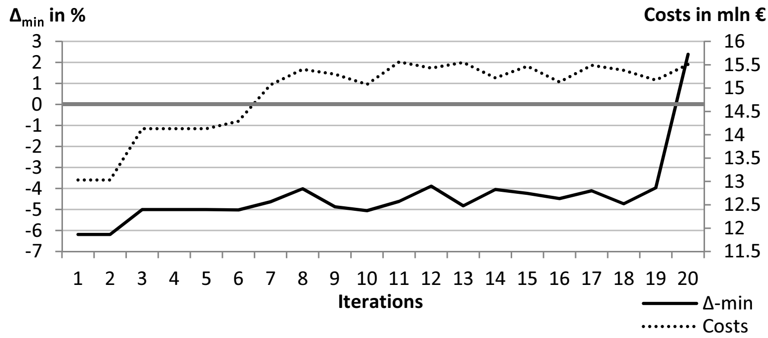


Figure 4.8: Costs and product quality over iterations in HOS for base scenario

with decreasing cut-off times, especially for mixed bouquets, costs only differ slightly. This is due to the fact that the network mostly changes with respect to goods flows while hub locations and process allocations remain the same.

Results for the second group of scenarios, in which the standard deviation of uncertain parameters is varied from 0 to 5% of their average, are summarised in Table 4.5. For the scenario with 5% uncertainty no feasible network design is found after 25 iterations and therefore this scenario is only discussed with respect to the number of iterations. Uncertainty increases costs and increases waste (the number of flowers disposed, because they have been buffered for too long, as percentage of the total number of flowers send to a process). Especially when direct transport is used from growers to the hub where supplied flowers are processed, waste increases. This is due to longer transport times which are more uncertain and cause more uneven arrivals of flowers at the hubs. Uncertainty has an ambiguous effect on the number of iterations needed to find a network design that can meet product quality requirements. Although improvement in product quality due to the simulation feedback increases with uncertainty, too much uncertainty makes it difficult to find a feasible network design. When the gap between MILP and simulation gets bigger it becomes more difficult for the HOS approach to adapt the MILP constraints effectively.

Table 4.4: Summary of scenarios differing in cut-off times

Cut-off time	Model	Costs (mln €)	Δ_{min} (%)		# hubs	# pro-cesses
			Mono bouquet	Mixed bouquet		
2x a day	MILP+	13.03	-0.87	-4.48	4	4
	HOS (5 iter.)	14.04	-0.87	0.22	5	5
4x a day	MILP+	13.03	-0.87	-2.39	4	4
	HOS (11 iter.)	14.04	-0.87	2.31	5	5
24x a day	MILP+	13.03	-0.87	-1.00	4	4
	HOS (13 iter.)	13.86	1.49	-0.67	5	5

Table 4.5: Summary of scenarios differing in uncertainty

Level of uncertainty	Costs (mln €)	Δ_{min} (%)		Waste[a] (%)	# iterations
		Mono bouquet	Mixed bouquet		
None	14.04	-0.87	0.22	0	5
1% (base)	15.51	2.39	2.84	18	20
2%	15.51	0.21	0.92	17	7
5%	16.22	-6.25	-9.68	5	25

[a] $\frac{\text{\# flowers disposed}}{\text{\# flowers send to processes}} \cdot 100$

Results for the third group of scenarios, in which network structures are changed, are summarised in Table 4.6. Spread in retailer locations and distinctiveness in transport costs and temperature do not affect the functioning of the HOS approach in these instances. However, distinctiveness in hub locations does. MILP solutions mostly change in the choice of locations and not much in the number of locations, but when distinctiveness of locations is low MILP solutions change more in the number of locations and the approach is less effective. Therefore, the usefulness of the HOS approach depends on the way the network is changed as a result of updated constraints.

Table 4.6: Summary of scenarios differing in network structure

Network structure	Model	Costs (mln €)	Δ_{min} (%)		# hubs	# pro-cesses
			Mono bouquet	Mixed bouquet		
Base structure	MILP+	13.03	-4.64	-6.19	4	4
	HOS (20 iter.)	15.51	2.39	2.84	5	5
Overlap grower-retailer regions	MILP+	11.57	-3.83	-5.94	4	6
	HOS (17 iter.)	13.05	2.20	0.51	4	6
Equal hub and process times	MILP+	12.32	-3.63	-5.35	4	4
	HOS (25 iter.)	15.05	-3.59	-4.44	5	6
Cooled, cheap transport	MILP+	11.49	-5.16	-5.15	4	4
	HOS (13 iter.)	12.67	2.02	3.19	3	3

4.7 Discussion & conclusion

In this chapter, an approach is presented to optimise a logistics network design for distributing multiple products that are highly perishable, such as cut flowers. The approach combines optimisation with simulation to accurately determine quality decay throughout a supply chain from growers to retailers. Next to decisions on hub locations and product flow allocations, an MILP model decides on the allocation of value adding activities (processes), which transform multiple raw materials into multiple final products at the hubs. Quality constraints are then included both in the MILP model, and in a hybrid approach that combines MILP and discrete event simulation. The models are demonstrated for different scenarios based on a European network for distributing flowers from the Netherlands.

A traditional MILP model without quality constraints, called MILP−, appears to result in low costs (related to locations, processes and transportation) but many products will arrive at the retailer with too low quality. This basic MILP model is extended with a constraint on approximated product quality, called MILP+. The product quality is approximated, while neglecting any dynamics that may happen due to products that get delayed (e.g. a process that cannot start because part of the input products are still in transport). MILP+ results in products delivered to the retailer with better quality, but, naturally, this comes at higher costs. By simulation the influence of uncertainty and dynamics in supplied quantity and quality is evaluated. It emerges that MILP+ results in a design that is infeasible as too many products with too low quality arrive at the retailer, or in a design that is feasible but too costly as product quality constraints are too conservative. To find a feasible solution or to improve it further, a hybrid optimisation-simulation approach is developed, called HOS. The HOS approach iteratively solves MILP+, checks by simulation the product quality that is delivered at the retailers and changes the product quality constraints in MILP+ relative to the gap between delivered and required product quality. HOS stops when a minimal cost solution of MILP+ is found which is feasible according to the simulation model. When the gaps between delivered and required product quality get larger, the updates of the MILP+ constraints get stronger and the HOS approach is more effective (as in the case of decreasing cut-off times). However, when the gaps become too large, the updates get too strong (overshoot) and it is more difficult for the HOS approach to adapt the MILP constraints effectively (as in the case of increasing uncertainty). Furthermore, the suitability of the HOS approach depends on the way the network is changed as a result of updated constraints. If change is mostly in the choice of locations and not so much in the number of locations the approach is very effective (as in the case where locations are distinct), but if the change is more in the number of locations the approach is less effective (as in the case where locations are similar). Issues encountered with the HOS approach mostly lie in the complexity of MILP+. The complexity, and with that runtime, of the MILP increases rapidly when more hubs have to be located or more processes have to be allocated. Further exploiting the HOS approach, the runtime is reduced by using the last found MILP+ solution as a warm start in the next iteration. Though, after a number of iterations the runtime of MILP+ can increase abruptly. As more and more product quality constraints get binding, they also introduce conflicts which make it harder to find an optimal or even feasible solution.

A new MILP model and HOS approach are developed. Future research could be directed to reducing the time needed to solve MILP+. Strategic decision problems, like network design, are not solved daily and are therefore allowed to have high runtimes from a practical point of view, but there is still room for improvement of the MILP+ runtimes. For example, part of a solution could be freezed or sub-solutions could be ruled out based on previous iterations, or approximate solution techniques could be developed, like those based on meta-heuristics. Another direction for future research could be to use a different formulation in the optimisation part of the hybrid approach. For example, stochastic programming could be used to capture part of the uncertainty in advance of the simulation part. Although a significant progress is made in approximating product quality in MILP+, future research could also be directed to further improving product quality approximations. Next to these directions for technical research, future research may also be related to the decision problem context. Decisions on process allocation are in this chapter based on the trade-off between conditions and costs of locations and transport. Future research could analyse how other factors, like lead time, influence process allocation and the interaction with product quality decay.

After all we conclude, that the HOS model is suitable in gaining insights in what the effect is of a strategic network design on its operational performance. The integration of strategic decision making and operational processes appears to be relevant especially for perishable products, like cut flowers and food products.

Appendix B: Linearizing Time Temperature Sum constraints

Auxiliary variables:

$$\begin{aligned}
\widetilde{ZH}_{ijp} \geq 0 &\quad = \widetilde{TTSH}_{ip}\widetilde{YH}_{ijp} \\
\widetilde{ZR}_{irp} \geq 0 &\quad = \widetilde{TTSH}_{ip}\widetilde{YR}_{irp} \\
\widetilde{Z}_{iqp} \geq 0 &\quad = \widetilde{TTSH}_{iq}Y_{ip}
\end{aligned}$$

Eliminating multiplications of binary and bounded non-negative variables in Equation (4.9), (4.11) and (4.12), this translates to:

$$\widetilde{ZR}_{irp} + ttsr_{irp}\widetilde{YR}_{irp} \leq maxtts_{rp} \qquad \forall i \in H, r \in R, p \in P \quad (4.13a)$$

$$\widetilde{ZR}_{irp} \leq \widetilde{YR}_{irp}up_{ip} \qquad \forall i \in H, r \in R, p \in P \quad (4.13b)$$

$$\widetilde{ZR}_{irp} \leq \widetilde{TTSH}_{ip} \qquad \forall i \in H, r \in R, p \in P \quad (4.13c)$$

$$\widetilde{ZR}_{irp} \geq \widetilde{TTSH}_{ip} - \left(1 - \widetilde{YR}_{irp}\right) up_{ip} \qquad \forall i \in H, r \in R, p \in P \quad (4.13d)$$

$$\widetilde{ZH}_{jip} + \left(ttsh_{jip} + ttsb_{ip}\right)\widetilde{YH}_{jip} \leq \widetilde{TTSH}_{ip} \qquad \forall i, j \in H, p \in P \quad (4.14a)$$

$$\widetilde{ZH}_{jip} \leq \widetilde{YH}_{jip}up_{jp} \qquad \forall i, j \in H, p \in P \quad (4.14b)$$

$$\widetilde{ZH}_{jip} \leq \widetilde{TTSH}_{jp} \qquad \forall i, j \in H, p \in P \quad (4.14c)$$

$$\widetilde{ZH}_{jip} \geq \widetilde{TTSH}_{jp} - \left(1 - \widetilde{YH}_{jip}\right) up_{jp} \qquad \forall i, j \in H, p \in P \quad (4.14d)$$

$$\widetilde{Z}_{iqp} + \left(tts_{ip} + ttsb_{ip}\right) Y_{ip} \leq \widetilde{TTSH}_{ip} \qquad \forall i \in H, p, q \in P \quad (4.15a)$$

$$\widetilde{Z}_{iqp} \leq Y_{ip}up_{iq} \qquad \forall i \in H, p, q \in P \quad (4.15b)$$

$$\widetilde{Z}_{iqp} \leq \widetilde{TTSH}_{iq} \qquad \forall i \in H, p, q \in P \quad (4.15c)$$

$$\widetilde{Z}_{iqp} \geq \widetilde{TTSH}_{iq} - \left(1 - Y_{ip}\right) up_{iq} \qquad \forall i \in H, p, q \in P \quad (4.15d)$$

Chapter 5

Logistics network configuration for perishable products: modelling -variability in- product quality decay

De Keizer, M., Akkerman, R., Grunow, M., Bloemhof-Ruwaard, J.M., Haijema, R., & Van der Vorst, J.G.A.J. Modelling product quality decay and its variability in logistics network design. *Submitted to an international journal.*

Abstract

The duration of logistics operations and the environmental conditions during logistics operations, significantly impact the performance of a logistics network for perishable products. When durations or temperatures increase, product quality decreases and more effort is required to deliver products in time and with the right quality. Different network configurations lead to different durations and conditions of transport, storage, processing, etc. Therefore, when making network configuration decisions, consequences for lead time and product quality should be taken into account. As decay of perishable products, for instance food, is often not uniform, variability in product quality decay also has to be considered. The aim of this chapter is to show how product quality decay as well as its variability can be integrated in a network configuration model. A new mixed integer linear programming formulation is presented, which positions stocks and allocates processes to maximise profit under quality constraints. It is applied to several test instances from the horticultural sector. Results show that a sufficient accuracy in modelling perishability is required. Different levels of decay lead to different network structures. Changing decay rates due to processing particularly affect the level of postponement. Variability in product quality causes a split in product flows with high and low product quality. All in all, it is shown that (variability in) product quality decay should be taken into account in network configuration as it significantly influences profit, especially when the supply chain includes processes that change the level of decay.

5.1 Introduction

Within a logistics network for perishable products, quality decay is a key consideration as it leads to value loss and waste. Quality decay is mainly determined by the duration of logistics operations (like transport, storage or processing) in combination with the temperature under which the operations are executed (Van der Vorst et al., 2009; Rong et al., 2011). Long durations prolong quality decay and high temperatures further accelerate this decay. Furthermore, biological diversity and exposure to different temperatures results in variability in the quality of perishable products. Technologies like RFID, Time Temperature Indicators (TTIs), controlled atmosphere storage rooms and refrigerated containers, can track and control product quality decay and variability in product quality throughout the logistics network. Information on product quality decay can be used to optimise stock rotation systems like 'first expired first out' (Jedermann et al., 2014), or to reduce waste by providing an accurate estimate of remaining shelf life (Grunow & Piramuthu, 2013). Information on variability in product quality can be exploited in serving different markets (Van der Vorst et al., 2011), e.g. high-end markets that demand high quality products can be charged a premium. The smaller the time scale, the more accurate product quality can be estimated. This makes inclusion of product quality information in long-term network configuration decisions a challenge (Akkerman et al., 2010a; Jedermann et al., 2014).

The design of a logistics network can be formulated as a hub location problem, which deals with the location of hubs and allocation of flows from suppliers to hubs, between hubs and from hubs to customers (Alumur & Kara, 2008). An important consideration in hub location problems is the positioning of stocks and processes. This has been extensively discussed in the literature and relates to the positioning of the customer order decoupling point (CODP), i.e. the strategic stock point where products are linked to specific customer orders (Olhager, 2010), as well as to the concept of postponement, i.e. the delay of processes that make products more customer specific (Forza et al., 2008). If products are stocked at de-central locations close to customers, lead times are shorter. If stock is pooled at more central locations, inventory costs are lower. If products are already customised, lead times are shorter. If customisation processes are postponed, stock of intermediate products can be flexibly used for different end products leading to lower stock levels. In general, the trade-off between lead time, location costs, transport costs and inventory costs thus shapes the decisions on hub locations as well as the decisions on CODP and postponement. To improve solutions, hub location problems and stock and process allocation problems should therefore be solved in an integrated way (Melo et al., 2009).

The time and costs trade-off is different in settings with perishable products. Decentralisation increases the number of hubs products go through, which increases handling time and in turn increases product quality decay and product quality variability. Furthermore, quality decay rates are often different before and after processing, which increases the relevance of CODP positioning and postponement decisions. For instance, when processed products decay at a faster rate than raw materials, storing raw materials is favoured from a product quality perspective (Van der Vorst, 2000). Alternatively, when processing decreases the quality decay rate, a short time until processing is favoured (Blackburn & Scudder, 2009).

The aim of this chapter is to develop a network configuration model that takes into account product quality decay and its variability, to be able to show the influence of these factors on hub location, CODP allocation and postponement. We do this using test instances from an illustrative fresh produce supply chain based on the floricultural sector.

The remainder of this chapter is organised as follows. Literature is discussed in Section 5.2. Then, the network configuration problem is described in Section 5.3. Section 5.4 formulates a Mixed Integer Linear Programming (MILP) model of the network configuration problem. Numerical experiments are presented and analysed in Section 5.5. Discussion and conclusion follow in Section 5.6.

5.2 Literature review

Hub location with CODP positioning and postponement forms the foundation for the problem studied in this research and related literature is first discussed. The extension of the problem lies in the incorporation of product quality decay. Therefore, the discussion is continued with supply chain research that takes product quality decay into account.

5.2.1 Hub location with CODP positioning and postponement

Strategic hub location problems have been widely studied (Aikens, 1985; Klose & Drexl, 2005; Alumur & Kara, 2008). To avoid sub-optimal solutions, strategic hub location is often integrated with tactical or operational stock and process decisions (Melo et al., 2009). CODP positioning is about determining the location of the stock point from which customer orders are fulfilled. One of the first studies on integrated hub and stock location problems, i.e. inventory-location problems, is the work by Shen et al. (2003). To incorporate risk pooling effects of centralised stock, they determine stock levels as a function of allocated product flows and add associated storage costs to the objective function. Here, they assume that all stock is located at the hub from which customers are directly delivered. This is the most common way to model inventory-location problems and is also applied in more recent studies, e.g. Shen & Qi (2007); Sadjady & Davoudpour (2012). Due to the non-linearities in the objective function, these models can be difficult to solve. Therefore, linearisations by piecewise linear functions and heuristic approaches have been proposed to effectively solve problem instances of real-life size (e.g Gebennini et al., 2009; Tancrez et al., 2012). Sun et al. (2008) further integrate CODP positioning in a hub location problem by deciding on the stock location as well as determining whether raw material, intermediate or finished products should be stored. They develop an integer linear programming model which minimises costs while guaranteeing on-time delivery to customers.

Integration of hub location with postponement encompasses the identification of processes and their location in the supply chain. Caro et al. (2012), for example, develop a model that allocates processes to existing plants for a case in the food-processing industry. They include typical process industry characteristics like uncertainty in process yields. Hammami et al. (2009) develop an MILP that determines the location of processes as well as what type of technology should be used. They test their model with an illustrative case in the automotive industry. Guericke et al. (2012) study a similar problem for the apparel industry. As this industry is characterised by stochastic demands and long transport times, they develop a stochastic MILP.

Decisions on stock and process allocation significantly influence the performance of a logistics network. Quite some research compares the performance of different CODPs and levels of postponement through simulation or case studies (e.g Olhager, 2010; Hedenstierna & Ng, 2011). Only few try to optimise the performance, for example by modelling CODP positioning and postponement in an MILP formulation. You & Grossmann (2008) present a detailed multi-period mixed integer non-linear programming model that combines hub location with process allocation, production planning and stock level decisions. They assume there is stock at the hub from which the customers are directly delivered (i.e. the CODP) and calculate the lead time as the transport time from hub to customer plus additional production time in case of stock-out. The production time is a result of process allocation. The probability of a stock-out is the result of the stock level decisions and demand distributions. Hammami & Frein (2013) present a similar multi-period model, but incorporate the lead time as a constraint. They approximate the lead time as the transport time and remaining production time from the CODP up to the customer for a representative order. Due to the high complexity of the integrated problem only small to medium-sized problem instances have been solved.

The literature shows that the integration of stock and process allocation decisions in a hub location problem improves network configuration. The challenge is to develop models that can be solved for problems of real-world size.

5.2.2 Modelling supply chains with product quality decay

Product quality decay is often incorporated in the modelling of supply chains at a tactical or operational level (e.g. Van der Vorst et al., 2009). For an overview of planning and inventory models, we refer to Ahumada & Villalobos (2009); Amorim et al. (2011); Bakker et al. (2012); Pahl & Voß (2014). Exponential decay, as commonly assumed, thereby provides a means to analytically incorporate product quality decay. As an alternative, Rong et al. (2011) present a more generic approach in which they classify product flows based on discrete quality levels. Product quality of the products, needed for the classification, can be determined using any product quality decay function. Tactical decision problems also include the modelling of postponement and decoupling points in supply chains (Akkerman et al., 2010b; Kilic et al., 2013). Postponement is especially important when decay rates change due to processing (Blackburn & Scudder, 2009). Blackburn & Scudder (2009) assume that quality decay slows down after processing (i.e. cooling) and model this using an exponential function with different rates. They show that the segments in the supply chain where decay is high should be managed responsively, and segments in the supply chain where decay is low should be managed efficiently.

There is a rich body of literature on strategic hub location, but work that takes perishability of products into account is limited (Akkerman et al., 2010a). Hwang (2004) study a set-covering location problem in which products deteriorate (or ameliorate) during transport. Assuming an exponential decay rate, the probability that products deplete during transport from a hub to a customer, is used to determine the fraction of the customer demand that can be covered from that hub. They then require that a given fraction of customer demand is covered with a minimum probability. They show how more hubs are located when the demand fraction or the decay rate increases. Zhang et al. (2003) determine quality decay on paths from supplier to customer in a logistics network using a first order kinetics model. They use tabu-search to find a solution in which the paths with the largest product quality decay can still satisfy quality requirements. They show that paths first incorporate two hubs to benefit from efficient transport between hubs. When product quality requirements tighten, the hubs are excluded from the paths and direct shipments between supplier and customer arise. Recently, Hasani et al. (2012) integrated hub and stock location decisions taking perishability of products into account. They develop a model that simultaneously locates hubs and allocates stocks by selecting warehouses. To model perishability, they set a maximum time that products can be in stock and add disposal costs to the objective function for products that pass the time limit. They focus on the effect of uncertainty in demand and purchasing costs rather than on the effect of product perishability. Using robust optimisation, they show that although costs increase due to uncertainty in the supply chain, a more stable network is provided. Yu & Nagurney (2013) integrate hub and process location. They develop a network-based model to select process types and locations, production technologies and warehouse locations. The model consists of nodes and links, where the flow on links is the number of products that flow from start node to end node taking into account the loss in products due to decay from start node to end node. Defining different markets and different products, they show that profitability can be improved by differentiating product prices based on product quality.

To the best of the authors' knowledge there is no research on integrated hub location and stock and process allocation problems that captures the dynamics of product quality decay. Next to the actual decrease in quality, this includes the variability in product quality decay, as well as the increase or decrease in the rate of decay resulting from processing the product.

5.3 Problem description

The structure of the network configuration problem, as reflected in food and fresh produce logistics networks and studied in this chapter, is depicted in Figure 5.1. Via one or more hubs, products of multiple types are supplied by multiple suppliers and distributed to multiple customers. Each hub can have different functionalities: it can just cross-dock products, it can store products, it can process products, or it can store and process products. The decisions to be taken in the model are (1) which hubs to open, (2) how to allocate flows from suppliers to hubs, between hubs and from hubs to customers (multiple allocation), (3) where to process (postponement) and (4) where to keep stock (position the CODP).

While products move through the network, product quality decreases during transport, storage and processing (Figure 5.1 for an illustrative network). Each product starts with a certain product quality level at the supplier (A and B), which can vary for different products and different suppliers due to differences in cultivars and differences in weather and growing conditions for agricultural products, among others. Then, with each logistics operation product quality decreases depending on the operations characteristics and the decay rate of the product. When products are transported from a supplier to a hub, the conditions during transport and the duration of the transport cause a quality decay. Furthermore, when products are stored (C) product quality decreases as a result of the storage conditions and duration. Moreover, processing could change the decay rate of products. This could be the combination (or assembly) or products in a process (D), such as combining ingredients into a meal or flowers into a bouquet. Here, the quality of the output product not only depends on the conditions and duration of the process, but also on the quality of the input products (a product is assumed to be as good as its worst component). Finally, products are transported to a customer (E and F), which again decreases product quality depending on conditions during transport and duration of transport.

For all logistics operations, average decrease in product quality is determined using a quality decay function. However, depending on how well operations can be controlled, there can be variability in product quality decrease. If cooled air in a truck cannot properly circulate, different spots in the truck can have different temperatures which can lead to variability in product quality decay; or if the doors to a cooled storage room are frequently opened the temperature will vary inside which can also lead to variability

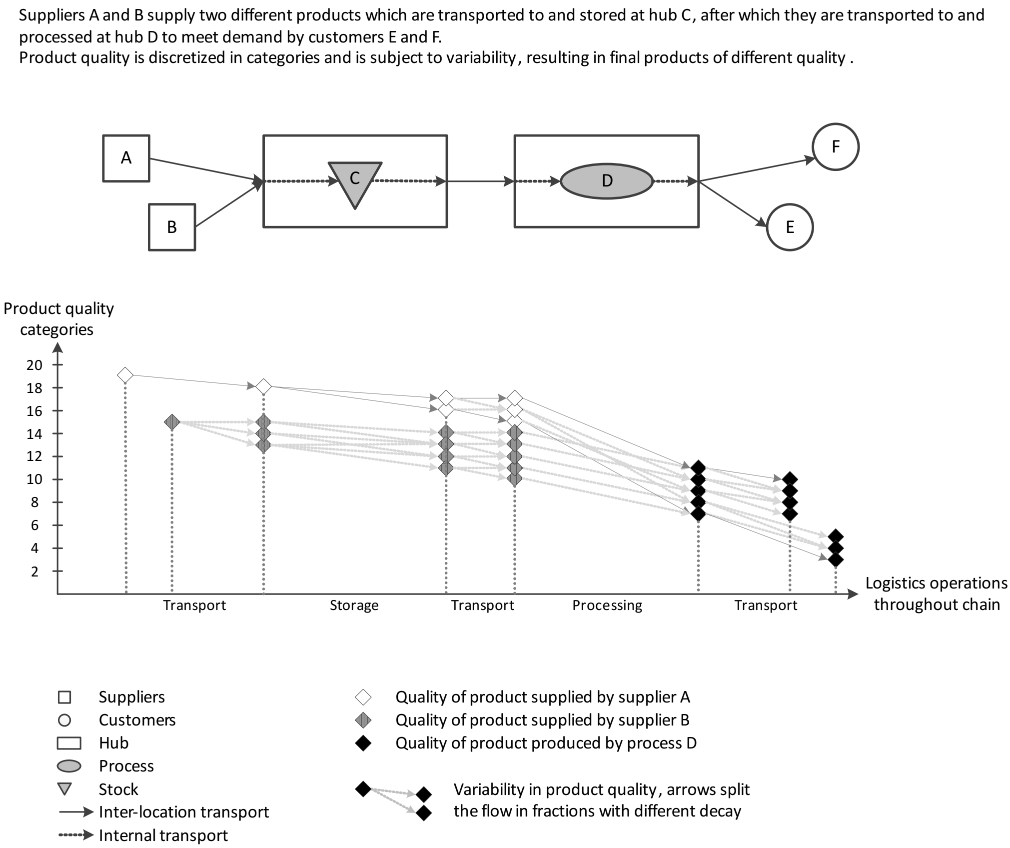


Figure 5.1: Illustrative network configuration and subsequent examples of product quality decay

in product quality decay. Products with the same product quality at the start of a logistics operation can thus have different product quality after transport or storage. Altogether, the configuration of a logistics network determines the chain of logistics operations and thus the final product quality of products delivered to the customers as well as the variability in product quality.

Common for food and fresh produce industries, is that there are different types of markets. In this case: a primary market, which is demand-driven; and a secondary market, which is supply-driven. These markets differ in trade mechanisms, lead times and product quality requirements. Primary customers trade one-on-one and order fixed quantities that should be met exactly. Secondary customers decide on quantity based on what is available and for what price. To provide these quantities, suppliers can supply up to a maximum quantity per product. Hence, secondary customer demands depend on supply quantities, primary customer demands and the price mechanism. Being part of a demand-driven market, primary customers require to be delivered within a given maximum lead time and should therefore be delivered from stock. More specifically, as the location of a stock point and the type of product stored determines the delivery time, each primary customer should be delivered from a stock point for which the delivery time is smaller than the maximum lead time. Primary customers also require a given minimum product quality.

The objective of the network configuration problem is to maximise annual profit resulting from sales revenues at the customer locations minus logistics costs (investment and operational costs) of the logistics network from suppliers to customers. The final product quality affects revenues earned at customer locations. On the one hand, primary customers pay a fixed price, if the required minimum product quality is achieved, and nothing, if it is not achieved. On the other hand, secondary customers are price sensitive to product quality which means that revenue increases with product quality. Costs include opportunity costs due to investment in hubs, processes and stocks, transportation costs and unit processing and storage costs.

The outlined problem comprises different product and market related factors, which influence the network configuration, and in turn influence the product quality delivered at the customers. A model should thus be formulated that incorporates the different factors, i.e. lead time requirements, level of product quality decay, variability in product quality decay, minimum product quality requirements and price sensitivity to product quality. In addition, the model should support analyses of network configurations, i.e. hub location and stock and process allocation, and their performance, i.e. profit and product quality that can be delivered at customer locations.

5.4 Model formulation

Before the problem is translated into an MILP model formulation, two important modelling issues are highlighted. First, incorporation of the allocation of stock is described. Second, incorporation of product quality decay and variability is described.

A stock allocation is modelled as the decision to designate a hub as strategic stock point from which either raw, intermediate or finished products are directly available, and from where customer orders will be fulfilled (i.e. the CODP). A stock allocation determines the remaining processing time before the product can be delivered to a customer plus the transportation time to a customer. Therefore, for each customer demand that has a maximum lead time it can be determined which stock allocations can meet that lead time (see lt^*_{hqcp} in the parameter list). Each customer demand should then be linked to one of these feasible stock allocations. Furthermore, allocating stock to a hub implies that the hub holds safety stock and working inventory. Cost estimations for these stocks are included in the objective function:

- Uncertainty in demands that are linked to a stock allocation determine the level of risk pooling and with that the level of safety stock (ss) that is needed to be able to reach a certain service level (α): $ss = z_{\alpha/2}\sqrt{\sum_{d \in D} \sigma_d^2 L_d}$, where $z_{\alpha/2}$ is the standard normal deviate such that $P(z \leq z_\alpha) = \alpha$, D are the customer demands linked to the stock allocation which are assumed to be independent and normally distributed, σ_d^2 is the variance of daily demand for customer d and L_d is the delivery time to customer d (see also Shen et al., 2003). Multiplying the safety stock by annual holding costs per product gives stock investment costs. Similar to Shen (2005), products are grouped into product types and for each product type a piecewise linear approximation of the non-linear stock investment cost is incorporated in the objective function.
- As particularly safety stock is sensitive to the number and location of hubs (Nozick & Turnquist, 2001), working inventory costs are simply included as unit storage costs in the objective function. These unit storage costs also incorporate possible handling costs.

While products move through the network, product quality decreases due to time and temperature during transport, storage or processing. In operational problems this has been modelled by product quality categories (Rong et al., 2011), which is employed here for the strategic-tactical network configuration problem (Figure 5.1). Each product starts in a given product quality category at the supplier and for each logistics operation it shifts to an equal or lower quality category. The operations characteristics and the decay rate of the product define the mean drop in quality categories for a product. For processing, starting from the lowest quality category among the input products, a fixed, mean drop is assumed. Variability in product quality decay is modelled for transport and storage by defining a distribution around the mean drop. A flow of products that is transported or stored is then split in fractions where each fraction has a different drop according to the defined distribution (see c_{ijpuv} and cs_{hpuv} in the parameter list). This way of modelling product quality decay causes the number and width of product quality categories to determine the accuracy with which product quality decay is incorporated in network configuration.

5.4.1 Sets, variables and parameters

Sets:

S	set of suppliers
C^*	set of primary customers
C	set of secondary customers
H	set of hubs

L	$= S \cup C \cup C^* \cup H$; set of locations
T	set of product types (e.g. raw material, finished product)
P	set of products
T_p	$\subset T$; product type of product p
P_t	$\subset P$; products that are of product type t
P_p	$\subset P$; products needed to produce product p
$\overline{P}_p$	$\subset P$; products in which product p is used
R	set of processes
P_r	$\subset P$; subset of products that are produced with process r
$\{1,\ldots,V\}$	set of product quality categories, V is the highest category
$\{1,\ldots,N\}$	set of intervals in piecewise linear approximation of safety stock costs

Decision variables:

The decision variables are summarised in Figure 5.2. Two types of flows are defined: before and after products have been stored and linked to a customer demand. This ensures that primary customers are delivered from stock, and that flows of products that have been linked (denoted as linked products and indicated by an asterisk) are preserved up to the customer location.

$Y_h \in \{0,1\}$	hub h is open or not
$YP_{hr} \in \{0,1\}$	process r is allocated to hub h or not
$YS_{ht} \in \{0,1\}$	stock of product type t is allocated to hub h or not
$YSS_{htn} \in \{0,1\}$	demand variance of product type t at hub h falls in interval n or not

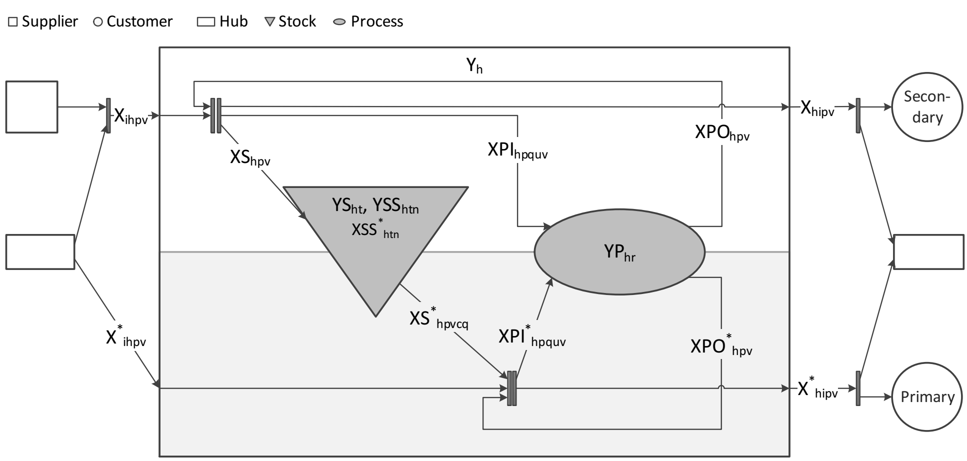


Figure 5.2: Decision variables in the network configuration problem

$X_{ijpv} \geq 0$ quantity of product p in quality category v at location i transported to location j

$X^*_{ijpv} \geq 0$ quantity of linked product p in quality category v at location i transported to location j

$XS_{hpv} \geq 0$ quantity of product p with quality category v put in stock at hub h

$XS^*_{hqvcp} \geq 0$ quantity of product q in quality category v retrieved from stock at hub h to be delivered as product p to customer c

$XSS^*_{htn} \geq 0$ demand variance for product type t at hub h in interval n

$XPI_{hqpuv} \geq 0$ quantity of product q in quality category u used to produce product p in quality category v at hub h

$XPI^*_{hqpuv} \geq 0$ quantity of linked product q in quality category u used to produce product p in quality category v at hub h

$XPO_{hpv} \geq 0$ quantity of product p in quality category v produced at hub h

$XPO^*_{hpv} \geq 0$ quantity of linked product p in quality category v produced at hub h

Parameters:

ur^*_{cp} unit revenue for delivering product p to primary customer c

ur_{cpv} unit revenue for delivering product p to secondary customer c in quality category v

fc_h fixed annual costs for opening hub h

fcp_{hr} fixed annual costs for allocating process r to hub h

fcs_{ht} fixed annual costs for allocating stock of product type t at hub h

$ucss_{htn}$ unit annual cost factor for demand variance of product type t at hub h within interval n

uc_{ijp} unit transport costs of product p from origin i to destination j

ucp_{hp} unit production costs of product p at hub h

ucs_{hp} unit storage costs of product p at hub h

sup_{spv} yearly supply of product p in quality category v by supplier s

dem^*_{cp} yearly demand of product p by primary customer c

σ^2_{qcp} daily demand variance of product p demanded by customer c stored as product q

v^*_{cp} minimum quality category demanded for product p by primary customer c

$$lt^*_{hqcp} = \begin{cases} 1 & \text{if lead time for product } p \text{ demanded by customer } c \text{ can be met by storing product } q \text{ at hub } h \\ 0 & \text{otherwise} \end{cases}$$

dem_{cp} demand of product p by secondary customer c

m_{qp}	quantity of product q in one unit of product p
mm_{qp}	fraction of product q in one unit of product p
M	big number
c_{ijpuv}	fraction of flow of product p starting at location i in quality category u and arriving at location j in quality category v
cs_{hpuv}	fraction of flow of product p put in stock in quality category u and retrieved from stock in quality category v at hub h
cp_{hp}	decrease in quality category due to producing product p at hub h
up_{htn}	upperbound interval n for demand variance of product type t at hub h

5.4.2 Objective and constraints

The objective (5.1) is to maximise profits. Profits equal returns from primary and secondary customers minus fixed location, process and stock costs, safety stock costs, transport costs and variable storage and process costs.

$$\begin{aligned}\max \quad & \sum_{c\in C^*}\sum_{p\in P} ur^*_{cp} \sum_{h\in H}\sum_{v=v^*_{cp}}^{V}\sum_{u=v}^{V} c_{hcpuv} X^*_{hcpu} + \sum_{c\in C}\sum_{p\in P}\sum_{v=1}^{V} ur_{cpv} \sum_{h\in H}\sum_{u=v}^{V} c_{hcpuv} X_{hcpu} \\ & - \sum_{h\in H} fc_h Y_h - \sum_{h\in H}\sum_{r\in R} fcp_{hr} YP_{hr} - \sum_{h\in H}\sum_{t\in T}(fcs_{ht} YS_{ht} + \sum_{n=1}^{N} ucss_{htn} XSS^*_{htn}) \\ & - \sum_{i\in L}\sum_{j\in L}\sum_{p\in P}\sum_{v=1}^{V} uc_{ijp}(X_{ijpv} + X^*_{ijpv}) \\ & - \sum_{h\in H}\sum_{p\in P}\sum_{v=1}^{V}(ucs_{hp} XS_{hpv} + ucp_{hp}\cdot(XPO_{hpv} + XPO^*_{hpv}))\end{aligned} \tag{5.1}$$

The first constraints are supply and demand constraints. Equation (5.2) ensures that the quantity transported from a supplier to hubs cannot be more than what the supplier can supply. Equation (5.3) ensures that primary customers get exactly the quantity they demand with a minimum product quality ($w \in V_v^+$). This takes into account that quality at the hub can be higher ($u \in V_w^+$) than quality at the customer due to transportation. Equation (5.4) ensures that the quantity transported from hubs to a secondary customer cannot be more than a given maximum irrespective of the product quality.

$$\sum_{h\in H} X_{shpv} \le sup_{spv} \qquad \forall s\in S, p\in P, v\in\{1,\dots,V\} \tag{5.2}$$

$$\sum_{h\in H}\sum_{v=v^*_{cp}}^{V}\sum_{u=v}^{V} c_{hcpuv}X^*_{hcpu} = dem^*_{cp} \qquad \forall c\in C^*, p\in P \quad (5.3)$$

$$\sum_{h\in H}\sum_{v=1}^{V}\sum_{u=v}^{V} c_{hcpuv}X_{hcpu} \leq dem_{cp} \qquad \forall c\in C, p\in P \quad (5.4)$$

The (linked) flows into a hub and out of a hub have to be in balance, which is depicted in Equation (5.5) and (5.6). The inflow for a hub consists of supply of the product by a supplier or by another hub, taking into account that quality at the origin can be higher than quality at the destination due to transportation. Furthermore, products can be produced by a process or retrieved from stock in case of linked products inflow. The outflow for a hub consists of distribution of the product to another hub, to a customer, to a process or to stock in case of non-linked products outflow. In case of processing, the quality of the product produced is at most the quality of the input product minus the quality decay due to processing.

$$\sum_{i\in S\cup H\setminus h}\sum_{u=v}^{V} c_{ihpuv}X_{ihpu} + XPO_{hpv} = \sum_{i\in H\setminus h\cup C} X_{hipv} + \sum_{q\in \overline{P}_p}\sum_{u=1}^{v-cp_{hq}} XPI_{hpqvu} + XS_{hpv}$$
$$\forall h\in H, p\in P, v\in\{1,\ldots,V\} \quad (5.5)$$

$$\sum_{i\in H\setminus h}\sum_{u=v}^{V} c_{ihpuv}X^*_{ihpu} + XPO^*_{hpv} + \sum_{c\in C^*}\sum_{q\in \overline{P}_p} XS^*_{hpvcq} =$$
$$\sum_{i\in H\setminus h\cup C^*} X^*_{hipv} + \sum_{q\in \overline{P}_p}\sum_{u=1}^{v-cp_{hq}} XPI^*_{hpqvu} \qquad \forall h\in H, p\in P, v\in\{1,\ldots,V\} \quad (5.6)$$

Inflows and outflows for processes and stocks also have to be in balance. This is depicted in Equation (5.7) to (5.9). For processing it is taken into account that quality before production can be different from quality after production and that multiple products can be used to produce a product. For stock it is taken into account that quality before storage can be different from quality after storage.

$$XPO_{hpv} = \sum_{u=v+cp_{hp}}^{V} \frac{XPI_{hqpuv}}{m_{qp}} \qquad \forall h\in H, p\in P, q\in P_p, v\in\{1,\ldots,V\} \quad (5.7)$$

$$XPO^*_{hpv} = \sum_{u=v+cp_{hp}}^{V} \frac{XPI^*_{hqpuv}}{m_{qp}} \qquad \forall h\in H, p\in P, q\in P_p, v\in\{1,\ldots,V\} \quad (5.8)$$

$$\sum_{c\in C^*}\sum_{q\in \overline{P}_p} XS^*_{hpvcq} = \sum_{u=v}^{V} cs_{hpuv}XS_{hpu} \qquad \forall h\in H, p\in P, v\in\{1,\ldots,V\} \quad (5.9)$$

Primary customers require a guaranteed lead time and it is indicated which stock allocations can fulfill their requirements. Equation (5.10) and (5.11) ensure that enough products are stored to fulfill demand and only at stock points that are feasible and allocated. Furthermore, if stock is allocated for a product that is input to a process, Equation (5.12) ensures stocks for all input products are allocated in balanced quantities.

$$\sum_{h\in H}\sum_{q\in P}\sum_{v=1}^{V}\Big[XS^*_{hqvcp}\cdot mm_{qp}\Big] = dem^*_{cp} \qquad \forall c\in C^*, p\in P \quad (5.10)$$

$$XS^*_{hqvcp} \le M\cdot lt^*_{hqcp}\sum_{n=1}^{N} YSS_{ht_q n} \qquad \forall c\in C^*, p,q\in P, h\in H, v\in\{1,\dots,V\} \quad (5.11)$$

$$m_{q_2 p}\sum_{v\in V} XS^*_{hq_1vcp} = m_{q_1 p}\sum_{v\in V} XS^*_{hq_2vcp} \qquad \forall h\in H, c\in C^*, p\in P, q_1,q_2\in P_p \quad (5.12)$$

For the piecewise linearisation of safety stock costs, Equation (5.13) estimates the demand variance of demands that are linked to a stock allocation. Then, Equation (5.14), (5.15) and (5.16) ensure that the demand variance is distributed from interval 1 to N. Equation (5.17) ensures that an interval can only be covered if its lower interval is.

$$\sum_{c\in C^*}\sum_{p\in P}\sum_{q\in P_t} lt_{hqcp}\sigma^2_{qcp}\frac{\sum_{v=1}^{V} XS^*_{hqvcp}}{m_{qp}\cdot dem^*_{cp}} \le \sum_{n=1}^{N} XSS^*_{htn} \qquad \forall h\in H, t\in T \quad (5.13)$$

$$XSS^*_{htn} \le up_{htn}\cdot YSS_{htn} \qquad \forall h\in H, t\in T, n=1 \quad (5.14)$$

$$XSS^*_{htn} \le (up_{htn} - up_{ht(n-1)})\cdot YSS_{htn} \qquad \forall h\in H, t\in T, n\in\{1,\dots,N\} \quad (5.15)$$

$$\sum_{m<=n} XSS^*_{htm} \ge up_{htn}\cdot YSS_{ht(n+1)} \qquad \forall h\in H, t\in T, n\in\{1,\dots,N-1\} \quad (5.16)$$

$$YSS_{htn} \ge YSS_{ht(n+1)} \qquad \forall h\in H, t\in T, n\in\{1,\dots,N-1\} \quad (5.17)$$

Flows of products can only exist if hubs are open or processes allocated, which is depicted in Equation (5.18) and (5.20). Equation (5.21) and (5.22) ensure that processes and stocks can only be allocated if a hub is open.

$$\sum_{p\in P}\sum_{v=1}^{V}\Big[\sum_{i\in H\setminus h\cup C} X_{hipv} + \sum_{q\in \overline{P}_p}\sum_{u=1}^{v-cp_{hp}} XPI_{hpqvu} + XS_{hpv}\Big] \le M\cdot Y_h \qquad \forall h\in H \quad (5.18)$$

$$\sum_{p\in P}\sum_{v=1}^{V}\Big[\sum_{i\in H\setminus h\cup C^*} X^*_{hipv} + \sum_{q\in \overline{P}_p}\sum_{u=1}^{v-cp_{hp}} XPI^*_{hpqvu}\Big] \le M\cdot Y_h \qquad \forall h\in H \quad (5.19)$$

$$\sum_{p\in P_r}\sum_{v=1}^{V}(XPO_{hpv} + XPO^*_{hpv}) \leq M \cdot YP_{hr} \qquad \forall h \in H, r \in R \quad (5.20)$$

$$YP_{hr} \leq Y_h \qquad \forall h \in H, r \in R \quad (5.21)$$

$$YS_{ht} \leq Y_h \qquad \forall h \in H, t \in T \quad (5.22)$$

The MILP model is implemented using IBM ILOG CPLEX Optimisation Studio 12.6 on a desktop with a 2.80 GHz Intel core i7 and 8GB RAM. To improve run times, redundant variables are filtered out and additional cuts are added to tighten the formulation. For example, linked product flow variables with a product quality index smaller than the minimum required product quality are removed and constraints 5.18 and 5.19 are split up to obtain a separate constraint per flow variable.

5.4.3 Determination of accuracy

Before the model can be used for analyses, accuracy with regard to product quality decay should be examined. When continuous quality decay is rounded down to fit a discrete quality category, paths in the network arise, for which the quality loss is underestimated. However, an increase in the number of quality categories goes along with an increase in the number of decision variables and calculation time. Above a certain number of categories, the rounding error is small enough to obtain a stable network configuration. Common to strategic decision problems, a trade-off has to be made between solution accuracy and effort. Based on the input data, the following measure for the relative rounding error can be calculated:

$$\epsilon_q = \frac{\frac{\sum_{o\in O}(v_o - \lfloor (v_o/v_{max})\cdot V \rfloor)}{|O|}}{v_{max}} \times 100\%$$

where O: set of all logistics operations (transport, storage, processing)
v_o: real product quality decay for logistics operation o
v_{max}: maximum quality decay for which V categories are defined

Accuracy with regard to safety stock should be examined in order to judge the validity of the results. Two issues need to be addressed:

- In the safety stock calculation fractions of the demand variance are summed instead of squares of fractions.
- The model comprises a level of aggregation to be able to solve problems of real-world size. Flows of products that are linked to a stock allocation are aggregated after they are retrieved from stock. As a consequence, the overall volume of stored products is preserved, however, when feasible stock allocations for demands overlap, the model could interchange stock allocations in the solution. In a post-processing step the stock allocations can be fixed without affecting the rest of the solution.

Based on the output data, the following measure for the safety stock error can be calculated:

$$\epsilon_s = \max_{h \in H, t \in T} \frac{S_{model} - S_{reference}}{S_{reference}} \times 100$$

where $S_{reference} = \sum_{q \in P_t} \sum_{p \in \overline{P}_q} \sum_{c \in C^*} \left[\frac{\sum_{v \in V} \widehat{XS}^*_{hqvcp}}{m_{qp} dem^*_{cp}} \right]^2 \sigma^2_{qcp} lt_{hqcp}$

$S_{model} = \sum_{q \in P_t} \sum_{p \in \overline{P}_q} \sum_{c \in C^*} \left[\frac{\sum_{v \in V} XS^*_{hqvcp}}{m_{qp} dem^*_{cp}} \right] \sigma^2_{qcp} lt_{hqcp}$

$\widehat{XS}^*_{hqvcp}$ = stock allocation for demand of product p by customer c after post-processing

Generally, the error in the safety stock estimation increases when stock is split over more locations and when more demands are split over multiple stock allocations. Together with the intervals chosen in the piecewise linear function for the safety stock costs and the share of the safety stock costs in the total fixed costs, it determines whether or not network configuration decisions will be affected.

5.5 Numerical experiments

A base scenario is defined as starting point for the numerical experiments. Then, to test the model for computational efficiency, problem instances of different size are solved. Furthermore, the model is run with different parameter settings in a sensitivity analysis.

5.5.1 Base scenario

Characteristics of the floricultural sector have been used to define products, processes, locations and parameters. A selection is made of four flower cultivars, which can be arranged as bouquets in two different ways and which can subsequently be packaged. As a result, three types of products (flowers, bouquets and packaged bouquets) and two types of processes (bouquet making, packaging/labelling) are distinguished. Hubs, suppliers and customers are located in a 2000x2000 grid (roughly the size of the central part of Europe in kilometers), on which the locations of suppliers (15), primary customers (12) and secondary customers (18) are chosen randomly. Suppliers supply flowers, primary customers demand bouquets or packaged bouquets, and secondary customers demand flowers. With respect to costs, as a bouquet takes more volume than the sum of volumes of flowers in it, a fixed multiplier is used to turn costs of flowers into costs of bouquets for storage and transport. Furthermore, transport costs are lower for transport between hubs. The more processes are executed before products are stored, the higher the costs of locked-up capital. Therefore, costs are higher for storage of processed products than for storage of raw materials.

Similar to shelf life for food products, the indicator for product quality of cut flowers is vase life, i.e. the number of days that flowers can be kept on a vase at room temperature which is generally assumed to be 20 °C (Tromp et al., 2012). From the duration d (in days) of a logistics operation and the temperature T (in °C) under which it is executed, the loss of vase life Δv can be calculated for that operation according to the degree-days model (Tromp et al., 2012): $\Delta v = (d \times T)/20\,°\text{C}$. If x days of vase life can be lost throughout the logistics network, the product quality categories $\{1, \ldots, V\}$ evenly split the interval from 0 to x. The number of product quality categories lost in the logistics operation is then calculated by $\lfloor \Delta v \times (V/x) \rfloor$. Different decay rates can be applied for different product types (t) by multiplying Δv with a factor δ_t. The overall level of decay is controlled by the temperature during logistics operations.

5.5.2 Accuracy and computational performance

Five random problem instances of the base scenario are generated. Before the model is run, the relative rounding error due to the discrete quality scale (ϵ_p) is calculated for different numbers of quality categories. At 30 categories the error drops below 2% and subsequent increments of 10 categories decreases the error with less than 0.5%. Therefore, 30 categories is chosen as default setting for the product quality analysis. After the model is run, the safety stock error due to the linear approximation (ϵ_s) is calculated. As the errors are generally below 1%, it is affirmed that the model is sufficiently accurate with regard to safety stock costs.

To determine the computational properties, the problem instance size is increased in the number of products (ten flowers, five bouquets and packaged bouquets), the number of suppliers (50) and the number of customers (40 primary and 60 secondary). These instances are then solved for an increasing number of potential hub locations (5, 10, 15, 20) and an increasing number product quality categories (1, 10, 20, 30, 40). Table 5.1 gives the average run times for the problem instances (to prevent excessive run times, the relative MIP gap tolerance is set to 3% for large problem instances). An increasing number of potential hub locations and an increasing number of categories increases run time substantially. However, a higher number of product quality categories can positively influence the structure of the problem. Increasing the number of product quality categories decreases the rounding error and improves the detection of infeasible paths in the pre-processing steps. This limits the increase in the number of variables and constraints. Furthermore, symmetries created through rounding are removed with an increasing number of product quality categories, which can decrease run time.

The expanded problem instances are also used to test robustness of network configurations. The network configuration, $network^0$, determined with a given number of product quality categories V^0 is evaluated in the setting of another number of product quality categories V^+. For this, the model is run with V^+ categories, which results in

Table 5.1: Results when increasing the number of hubs and product quality categories

Scenario	Number of hubs	Number of product quality categories	MIP gap	Run time (hrs)	#variables	#binaries	#constraints	#nonzeros
Increasing number of hubs	5	10	0%	0.03	76053	60	28555	323833
	10	10	0%	1.16	161408	120	65884	685512
	15	10	0%	7.84	264690	180	113277	1136088
	20	10	3%	20.24	390165	240	180972	1703340
Increasing number of categories	15	1	0%	0.10	31030	180	34158	153906
	15	10	3%	3.66	264690	180	113277	1136088
	15	20	3%	13.75	514673	180	168497	2129289
	15	30	3%	42.40	781335	180	220860	3137314
	15	40	3%	38.48	856234	180	186732	3346886

profit π^+. Then, the locations and allocations of $network^0$ (the binaries) are fixed and the model is run again with V^+ categories, which results in profit π^0. The robustness of $network^0$ is given by $\Delta\pi = (\pi^+ - \pi^0)/\pi^0$. For illustrative purposes, a cross-comparison like this is given in Table 5.2. The first row shows that not incorporating product quality impacts profits. These results also substantiate the choice of using 30 product quality categories as default setting.

5.5.3 Sensitivity analysis

To analyse the impact of different product quality factors, a number of scenarios is defined (Table 5.3). As product quality decay is assumed to be determined by temperature settings, the first group of scenarios is based on overall temperature.

Table 5.2: Differences in profit when recalculating the profit of a configuration with increasing numbers of quality categories to show robustness

Base number of categories (V^0)	Increased number of categories (V^+)	Difference[a] $\Delta\pi = (\pi^+ - \pi^0)/\pi^0$
1	10	-2.0%
10	20	-0.2%
20	30	-0.6%

[a] π^+ = profit when V^+ categories are used
π^0 = profit when V^+ categories are used and (al)locations are fixed to configuration for V^0 categories

Characteristic for perishable products is the variability in product quality. The second group of scenarios is therefore based on variability distributions. For floricultural products, the quality of processed products, i.e. bouquets, is more difficult to preserve compared to unprocessed products, i.e. flowers. For perishable products in general, processing can slow down decay, e.g. by treatment or packaging. Therefore, the third group of scenarios is based on different decay rates before and after processing (which is done by setting different values for δ_t with $t \in \{flower, bouquet, packaged\}$).

Table 5.3: Overview of scenarios for sensitivity analysis

Description	Setting	Values			
Level of decay	Temperature	$T = 0\,°C$ (no decay), $2\,°C$, $4\,°C$, $6\,°C$, $8\,°C$			
Variability	Fractions	Average decay is given by uv (for transport from i to j of product p or for storing product p at hub h)			
		No:	$c_{ijpuv} = 1$		
			$cs_{hpuv} = 1$		
		Low:	$c_{ijpu(v-1)} = 1/2$ & $c_{ijpu(v+1)} = 1/2$		
			$cs_{hpu(v-1)} = 1/2$ & $cs_{hpu(v+1)} = 1/2$		
		Medium:	$c_{ijpu(v-2)} = 1/2$ & $c_{ijpu(v+2)} = 1/2$		
			$cs_{hpu(v-2)} = 1/2$ & $cs_{hpu(v+2)} = 1/2$		
		High:	$c_{ijpu(v-3)} = 1/2$ & $c_{ijpu(v+3)} = 1/2$		
			$cs_{hpu(v-3)} = 1/2$ & $cs_{hpu(v+3)} = 1/2$		
Decay rates	Decay rate factors		δ_{flower}	$\delta_{bouquet}$	$\delta_{packaged}$
		Fast increase	0.6	1	1.4
		Slow increase	0.8	1	1.2
		No change	1	1	1
		Slow decrease	1.2	1	0.8
		Fast decrease	1.4	1	0.6

Note: Results are comparable for all problem instances, but as there are different contradictory ways to handle product quality decay, averages of the indicators neutralise the impact, therefore an instance is selected to discuss the scenarios

The changes in network configurations are discussed with regard to network structure, level of postponement and position of the CODP. The structure of the network is denoted by the number of hubs, the number of hubs to which processes are allocated and the number of hubs to which stocks are allocated. An increase in the level of postponement is observed when processes are executed further downstream the supply chain (closer to the customers). Therefore, the level of postponement is indicated by the inverse of the average distance from processes to primary customers. A change in the position of the CODP is observed when the allocated stock point for a primary customer changes. The CODP is then indicated by the average lead time from the allocated stock point to the primary customer, where the lead time consists of transport time and possibly processing time (e.g. when flowers are stored and bouquets are ordered). The performance of networks is expressed in profit and product quality for primary and secondary customers. Product quality is given by the lowest to highest quality of the products delivered to the customers.

Level of product quality decay

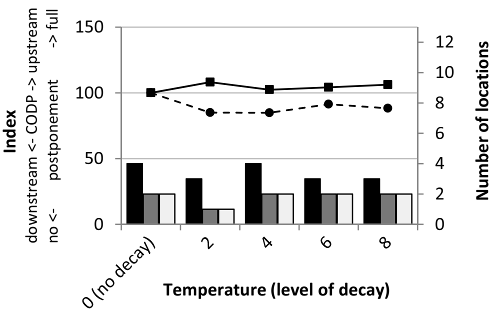
Figure 5.3a shows the changes in network structure, postponement and CODP positions for an increasing temperature, i.e. increasing level of decay. It indicates that there are different ways to cope with quality decay in network configuration. On the one hand, as seen in the changes when the temperature increases from 0 °C to 2 °C or from 4 °C to 6 °C, the network can be centralised to decrease handling time and hence decay (similar to Zhang et al. (2003)). On the other hand, as seen in the changes when the temperature increases from 2 °C to 4 °C, more hubs can be opened to decrease transport times and hence decay (similar to Hwang (2004)). When temperature increases from 0 °C to 2 °C, hub locations at the customer side are joined, which moves the CODP upstream and decreases the level of postponement. When temperature increases from 4 °C to 6 °C, hub locations at the supplier side are joined. This does not really affect the CODP and the level of postponement as processes are allocated to hubs close to the customers. If feasible in combination with the hub locations and level of postponement, the CODP is moved upstream to benefit from risk pooling at more central hubs.

When decay increases, both product quality and profit decrease (Figure 5.4a). The highest quality products are increasingly needed to fulfill the primary market requirements. This reduces the supply of high quality products for the secondary market, which decreases revenues. In addition, costs increase when the network is centralised and decrease when the network is decentralised.

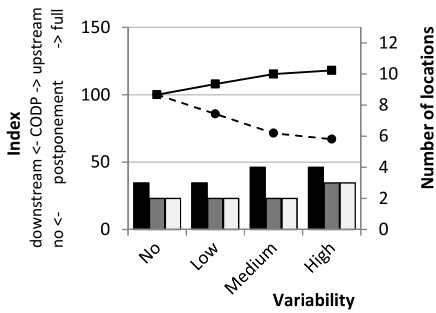
Variability in product quality decay

Figure 5.3b shows the changes in network structure, postponement and CODP positions for an increasing level of variability in product quality. It indicates that variability particularly affects the position of the CODP and the level of postponement. To hedge against the risks, stocks and processes are moved upstream to more central hubs. For a medium to high level of variability, this requires that an additional hub is opened.

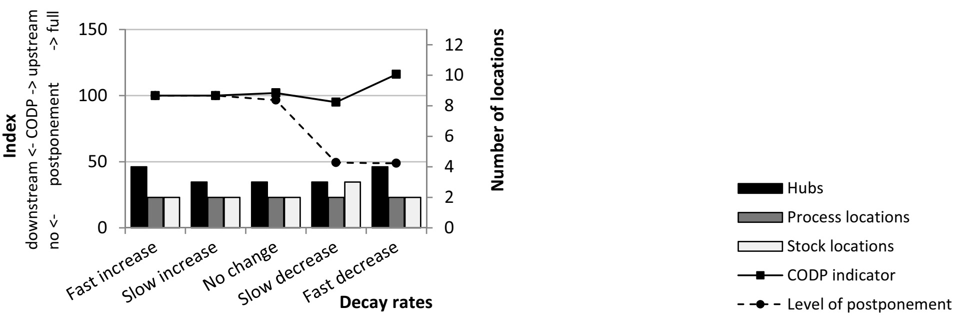
With an increased level of variability, a separation of highest and lowest quality products arises. On the one hand, high quality products are distributed to the secondary market to earn a higher revenue than in the primary market. On the other hand, low quality products are distributed to the secondary market as these products cannot fulfill the primary market requirements. When increasing the level of variability from low to medium, profit increases particularly due to an increase in revenues from the high quality products for the secondary customers (Figure 5.4b). When further increasing the level of variability from medium to high, the supply of high quality products remains the



(a) Network changes due to increasing temperatures (levels of decay)



(b) Network changes due to increasing variability



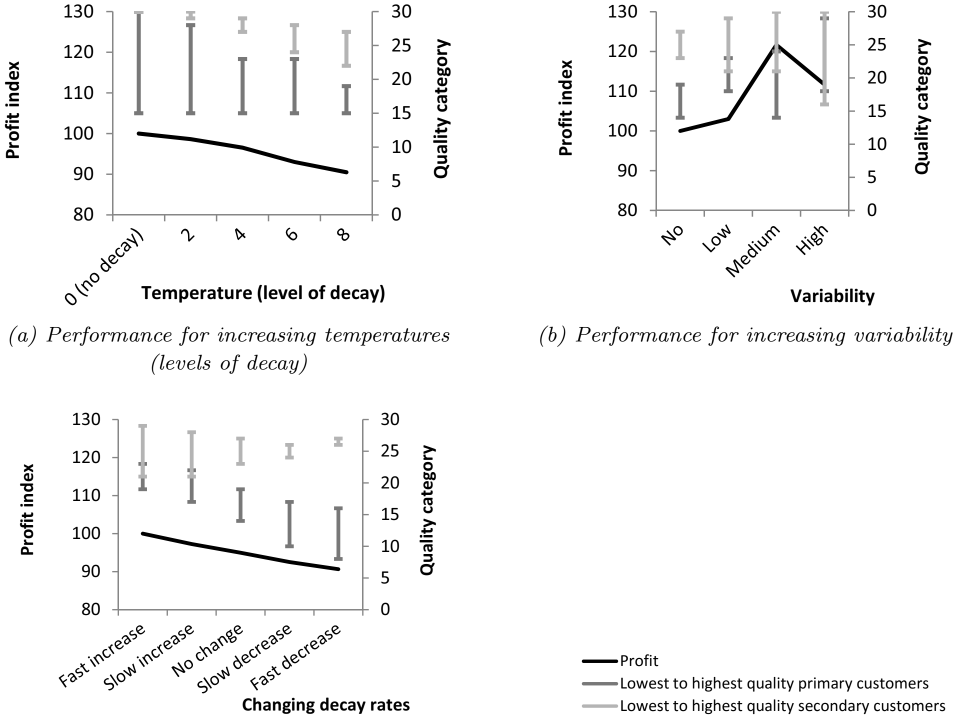
(c) Network changes due to changing decay rates

Figure 5.3: Impact of different product quality parameter settings on the network configuration

same, while the supply of low quality products increases. The revenue increase is then partially offset by a revenue decrease from the low quality products for the secondary customers. Overall, an increase in the level of variability increases the range of product quality for primary customers and causes more outliers in the range of product quality for secondary customers.

Increasing and decreasing decay rates

Figure 5.3c shows the changes in network structure, postponement and CODP positions from fast increasing to fast decreasing decay rates. Two resolutions can be identified to cope with increasing decay rates due to processing. First, when processes increase decay, the level of postponement is high and processes are moved downstream towards the customers in order to process as late as possible. Second, storage of bouquets and packaged bouquets is avoided. When processes decrease decay, the level of postponement is decreased. Processes are moved upstream towards the suppliers and bouquets are



(a) Performance for increasing temperatures (levels of decay)

(b) Performance for increasing variability

(c) Performance for changing decay rates

Figure 5.4: Impact of different product quality parameter settings on network performance

stored. This implies that a larger part of the supply chain can be focused on cost effectiveness (Blackburn & Scudder, 2009). This is reflected in the upstream move of the CODP to more central hubs, which increases the benefits of risk pooling.

Profit as well as product quality decrease when processing decreases decay rates compared to when processing increases decay rates (Figure 5.4c). As bouquets are more expensive to store and transport than flowers, moving processes downstream decreases costs. However, when processes decrease decay rates, moving processes upstream increases product quality. Processes are allocated to serve primary customers and primary customers do not pay for higher product quality, therefore, the cost decrease outweighs the product quality increase. Although the level of postponement is lower in the scenarios with decreasing decay rates compared to the scenarios with increasing decay rates, it is not low enough to prevent a decrease in product quality. Profit furthermore decreases as a result of a decrease in revenues from secondary customers. This is caused by the gradual increase in the decay rate of the flowers that are supplied to secondary customers.

What emerges from the results is that the network changes and performances are not straightforward. The integration of hub location with process and stock allocation, and the transport and storage cost differences between flowers and (packaged) bouquets, cause a complex trade-off between profit and product quality.

5.6 Discussion and conclusion

In this chapter, a new MILP model is presented for designing and configuring a logistics network for distribution of perishable products which takes into account product quality decay and its variability. The main decisions are where to locate hubs, at which hubs to process, at which hubs to keep stock and how to allocate flows of products from suppliers via hubs to customers. Stock allocation decisions are included for customers who require a given maximum lead time. Furthermore, the model keeps track of product quality throughout the network based on decay due to duration and temperature of logistics operations. More importantly, by also including a spread in the decay, variability in product quality is incorporated in a relatively simple way. It contributes to the research gap of the interaction between the operational issues of quality decay and the strategic decisions involved in logistics network configuration (Akkerman et al., 2010a).

The model is tested for various scenarios from small to real-world size and based on a logistics network for cut flowers. Results show that there is a clear trade-off between the accuracy in modelling perishability, i.e. the number of product quality categories used, and the effort to solve the model. As not taking into account perishability can impact profit significantly, input data and robustness of networks should be examined when the model is used for analyses. The level of decay particularly affects the hub locations and the level of centralisation in the network. Variability in product quality causes a split in product flows with high and low product quality, thereby creating a secondary market that acts as high-end market and as market for low quality products that cannot be sold at the primary market. When processing increases or decreases decay, it mainly affects the level of postponement.

An advantage of the model is that it is able to capture the basics of variability in quality decay without having to include stochastic aspects in models that are already complicated enough in deterministic settings. Another advantage is the flexibility in modelling perishability. Any type of decay that can be quantified, can be modelled. In this chapter, decay is based on a time-temperature model, but also other environmental conditions like humidity could be taken into account. This way the model can be easily applied to other perishable products.

The results in this chapter show that there are different ways to cope with product quality decay in network configuration. Future research could be focused on case applications to get more insight in the effects of product quality on network configuration and its performance. Especially the differences in impact at a strategic and operational level, as the consequences of product quality decay particularly materialise at the operational level. In the same line of reasoning, the decisions in the integrated problem could be extended with operational decisions to further optimise the complete network. Next to variability in product quality, also uncertainty in product quality and quantity is apparent in perishable product logistics networks. Future research could focus on stochastic models to analyse when it suffices to incorporate variability and when a stochastic setting is required.

Chapter 6

Effective logistics networks for the distribution of cut flowers in supply and demand driven supply chains

De Keizer, M., Bloemhof-Ruwaard, J.M., Haijema, R., & Van der Vorst, J.G.A.J. Logistics networks for perishable products in supply and demand driven chains. *Submitted to an international journal.*

Abstract

Especially due to globalisation and virtualisation (web-shops and virtual auctioning) customer requirements are changing, e.g. shorter lead times, smaller order sizes and higher product quality. The Dutch floricultural sector, a network of growers, traders, auctions, logistics service providers and customers, has to respond to these changes. The sector has to move from a mostly supply driven to a more demand driven supply chain. This means that a different type of logistics network, with respect to hub locations and process and stock allocations, is needed. The feasibility and suitability of a logistics network is however affected by the perishability of cut flowers. The aim of this chapter is to develop a network characterisation for supply and demand driven chains for perishable products. The characterisation is based on optimal networks that are designed and configured for each type of chain using a hybrid optimisation and simulation approach. Results show that the optimal logistics network for perishable product supply chains is especially driven by the trade-off between responsiveness and product quality. The network should be dense enough to limit the transport time and product quality loss within the supply chain and close attention should be paid to the control of the stock points to limit the risk of spoilage and consequent stock-outs.

6.1 Introduction

The Dutch floricultural sector has a long tradition in offering and distributing cut flowers and potted plants to the European market. Cut flowers, which are cultivated worldwide, are mainly sold through auctions in the Netherlands and pushed to detail markets (i.e. specialised sales channel like florists and street trade). Consumers then come to the sales outlet to have a bouquet made from the flowers that are available from stock. The pivotal auction process in this supply driven chain is becoming increasingly virtual. Nowadays, buyers do not have to be physically present at the auction location, but can bid virtually on products using the internet. When the products are physically present at the auction location this is called 'buying at a distance'. 'Virtual auctioning' entails that buyers as well as products are not physically present at the auction location. As a consequence, commercial and logistics flows are increasingly disconnected. This increases the reach of the supply chain with respect to distances to growers and customers. Furthermore, it asks for a reassessment of the logistics network (De Keizer et al., 2015b).

Although detail markets still represent the main sales channel for cut flowers, the market share of retail (i.e. unspecialised sales channel like supermarkets and gas stations) is increasing (Van der Vorst et al., 2012). Moreover, e-tail (i.e. virtual sales channels like web-shops) is slowly emerging. These markets are much more demand driven and have more challenging customer requirements like high order frequency and small order size, fast delivery and guaranteed product quality. The differences in supply and demand driven chains result in differences in the configuration of associated logistics networks (Olhager, 2010).

The design of a logistics network is grounded by hub location decisions. In addition, adjusting from a mainly supply driven to a more demand driven chain implies a shift in the Customer Order Decoupling Point (CODP), i.e. the stock point from where the customer order process starts and where a product is tied to a specific customer order (Olhager, 2010). Hub locations thereby define potential CODPs, which creates a need to consider hub location and CODP decisions simultaneously. This translates into a logistics network problem consisting of hub location and flow allocation decisions as well as process and stock allocation decisions.

Insights have been gathered on how logistics networks and their performance differ between supply and demand driven chains (e.g. Ferreira et al., 2014). However, the influence of product perishability, as is the case for cut flowers, on both hub location and CODP decisions is not discussed. Therefore, the aim of this research is to derive a network characterisation for supply and demand driven supply chains for perishable products.

Different logistics networks for the cut flower supply chain network (SCN) are configured and evaluated in this chapter using a quantitative modelling approach. Building on the insights for general supply chains that do not have to deal with perishability, a case study approach is selected for validation and theory refinement (Dinwoodie & Xu, 2008). The case study is used to address the following research question: what are key considerations for logistics networks designed and configured for perishable product supply chains with different CODPs?

The remainder of this chapter is organised as follows. In Section 6.2, literature is discussed. Then, the case study is described in Section 6.3. Section 6.4 describes the model that is used. This is followed by analyses of the results in Section 6.5. Finally, Section 6.6 contains a discussion and conclusion.

6.2 Literature review

To be able to understand the triangular interaction between logistics network design, CODP allocation and product perishability, the three underlying mutual relationships are analysed. The interaction between logistics network design and CODP allocation is first discussed. Then, the influence of product perishability on respectively logistics network design and CODP allocation is discussed. Finally, the triangular interaction is summarised.

6.2.1 Logistics network design and CODP allocation

Logistics network design starts with hub location and flow allocation decisions. Based on these decisions, networks can be divided in line networks, centralised networks and de-centralised (collection and distribution) networks (Daganzo, 2005; De Keizer et al., 2014). Chopra & Meindl (2013) further specify network designs in retail storage with customer pickup (de-central), manufacturer storage with pickup (de-central), manufacturer storage with direct shipping (line), manufacturer storage with in-transit merge (central), distributor storage with package carrier delivery (central) and distributor storage with last-mile delivery (de-central).

The network typology of Chopra & Meindl (2013) specifies the location of stock-points. This relates to the position of the Customer Order Decoupling Point (CODP), i.e. the strategic stock point which separates the forecast-driven flow of products from the order-driven flow of products in the supply chain (Olhager, 2010). Logistics operations upstream of the CODP should be aligned to fulfill the requirements of the strategic stock-point, which are different from the market requirements. Logistics operations downstream of the CODP should be aligned to fulfill the requirements of the customer. The CODP not only determines the location of the stock, but also the type of stock, i.e. storing raw materials, intermediate products or finished products. When raw materials or intermediate products are stored at the CODP, it means that all or parts of the processes are postponed until customer orders are known. This is called Form

Postponement (FP), i.e. changes to the form of a product occur at the latest possible point in the supply chain (Forza et al., 2008).

Decisions on network design and CODP/FP affect the performance of the logistics network. The main performance indicators (Forza et al., 2008; Chopra & Meindl, 2013; Ferreira et al., 2014) can be divided in costs and responsiveness. Costs consist of facility, handling, transportation, warehousing, inventory and processing costs, among others. Responsiveness consists of fill rate, stock-outs rate, on-time delivery rate, back orders cycle time, response time, product variety, delivery flexibility (speed and completeness) and order specification flexibility, among others. Exemplary case studies are used to summarise the performance of different network designs and CODPs. For example, Cirullies et al. (2011) use a simulation-based assessment to evaluate the performance of different CODP positions in a supply chain with a plant, a hub and a distributor. They show that moving the CODP downstream improves the performance of the network with respect to response time. With respect to costs, the performance improves when the CODP is moved upstream. Bottani et al. (2014) analyse a network structure in which independent companies manage their processes and distribution separately. They compare this base structure with a redesigned structure in which there is central supply of packaging and central storage of finished products. They show that, although there is an additional facility which increases facility costs, the overall costs decrease with the new structure due to decreased transportation and especially inventory costs.

More generally, based on a multi-case study, Brun & Zorzini (2009) conclude that a rigid structure (i.e. CODP at the end of the supply chain) is especially suitable for supply chains with a low complexity of the processes and a low level of customisation. It is mostly focused on exploiting economies of scale in production and transportation. When the level of customisation increases, postponement becomes a profitable tool to increase product variety, while still profiting from economies of scale where possible. It also reduces risk and uncertainty costs. Daaboul et al. (2014) perform a case study in which they hypothesise different differentiation and decoupling points and calculate the value for the company as well as the perceived value for customers. They show that moving the CODP towards suppliers while increasing the level of postponement increases customer value, but decreases company value.

This overview shows that hub location and CODP allocation decisions are interconnected and should be considered simultaneously. Furthermore, it shows that costs and responsiveness are key indicators when analysing these decisions.

6.2.2 Logistics network design for perishable products

Perishable products have specific characteristics that put requirements on logistics operations. For example, products require specific physical distribution solutions (Fredriksson & Liljestrand, 2014). This makes delivery speed and geographical location an important issue. The value of the product could limit the transport possibilities and sourcing options. In case of agricultural products, the sourcing options are furthermore determined by natural conditions and product quality is established at the time of harvesting (cf. Fredriksson & Liljestrand, 2014).

The influence of product quality in an agricultural product supply chain is shown by Van der Vorst et al. (2009). Using discrete-event simulation, they show the trade-off between quality and costs for a supply chain in which either air transport or sea transport is used. Although air transport is more expensive, it can better preserve product quality than sea transport. Rijpkema et al. (2014) show the consequence of taking into account product quality when making decisions on dual sourcing. When including costs for shelf life losses, regular transport decreases and consequently expedited transport increases. This reduces shortages and waste and allows for a decrease in inventory levels. It also results in a higher remaining shelf life for the customers. Tsao (2013) show how product quality decay influences a hub network with regard to hub locations and replenishment cycle time for stocks at the hubs. When the decay rate of products increases, products spoil more quickly during storage and therefore the cycle time for stocks is decreased. To still maintain a substantial level of risk pooling, the number of customers served from a hub is increased and less hubs are located.

These examples support that product quality is influenced by the logistics network design and the logistics network design is influenced by product quality (Van der Vorst et al., 2009).

6.2.3 CODP allocation for perishable products

Like network design, the position of the CODP is affected by the perishability of products. In general, high demand uncertainty and a high level of product customisation move the CODP towards the suppliers and short expected lead time and high delivery reliability move the CODP towards the customers. In case of perishable products, long production throughput times and high uncertainty in supply and processing move the CODP towards the customers and the perishability of end products moves the CODP towards suppliers (Van der Vorst, 2000). Li et al. (2007) furthermore show that not just perishability, but the level of perishability (the deterioration rate) determines the move of the CODP towards suppliers. To do this, they developed an EOQ-based model in which they account for product losses due to spoilage during storage and compared the performance of two supply chains with different CODPs for different deterioration rates.

Sharda & Akiya (2012) use a discrete event simulation to show the trade-offs when moving the CODP towards the suppliers and increasing the level of postponement. They show how cleaning costs and finished product storage costs increase with postponement and how raw material storage costs and overall inventory costs decrease with postponement. The on-time order fulfillment also decreases with postponement.

Especially products with high shelf-life expiration costs benefit from postponement, although this is mostly related to demand volume and uncertainty rather than product perishability. McIntosh et al. (2010) argue that the potential of postponement depends on which customising processes are postponed. For food, for example, postponing packaging processes rather than production processes is more suitable. Factors like product decay, cleaning and legal requirements, can furthermore limit the options for postponement.

Altogether, the examples support that moving the CODP, including changing the level of postponement, affects product quality and that the position of the CODP is affected by product perishability.

6.2.4 Logistics network design and CODP allocation for perishable products

Different network designs have different trade-offs in facility costs, transportation costs, inventory costs, response time and flexibility. Likewise, different CODP allocations have different trade-offs in cost and responsiveness indicators. In the preceding literature review, it is shown how network design and the position of the CODP are each separately affected by perishability of products. The influence of perishability on integrated network design and CODP allocation, i.e. network configuration, is however not discussed in literature. Building on the knowledge of the separate topics, the aim of this research is to analyse the performance of different network designs with different CODPs for different levels of perishability of products. In line with the conclusions from the preceding literature review, network design and CODP allocation are optimised simultaneously. Furthermore, product quality decay is taken into account. Performance indicators for costs, responsiveness and product quality are selected to adequately analyse performance (Aramyan et al., 2007).

6.3 The cut flower supply chain network

This section describes the design of the case study and the characteristics of the case. Furthermore, scenarios are presented that will be analysed to evaluate logistics networks for supply and demand driven chains.

6.3.1 Case study design

In close cooperation with sector partners, the cut flower SCN was analysed and a representative supply chain was selected from the network. The representative supply chain was used to define case settings, to set the scope for the case and to collect relevant data. In a number of workshops with sector partners, the main developments for the cut flower SCN were determined. These developments were used to define broad-based scenarios for which it seemed interesting to determine an appropriate logistics network and to quantify the performance of that network. A model was developed that (i) determines optimal logistics network for the scenarios, and (ii) evaluates the logistics networks in order to quantify the performance. During the study, preliminary results and assumptions are discussed with sector partners.

6.3.2 Case description

Supply chain networks for agricultural products, like cut flowers, can be divided in two main types: networks for fresh products and networks for processed products (Van der Vorst et al., 2009). Three key differences are the length of the chain, the customers that are served and the processes executed. Next to growers, importers and logistics service providers, the first type of chain comprises auctions, wholesalers and exporters, where the second type of chain comprises processors. Fresh products are mostly delivered to specialty shops, while processed products are mostly delivered to retail chains. The processes executed in fresh product supply chains, i.e. handling, storing, packing, transport and trading, do not change the product except for the quality which can change due to environmental conditions. The processes executed in processed product supply chain use the raw material to produce products with a higher added value and possibly lower decay due to conservation or packaging.

The case in this chapter is of the first type. It concerns a wholesaler that sells cut flowers to retailers, wholesalers, importers and florists throughout Europe (France, Italy, Germany and Finland). The wholesaler acquires its cut flowers from growers throughout the world (South-America, Africa, Europe). The wholesaler has three central locations in the Netherlands (close to auction locations), however, all products bought are gathered at one hub location. The wholesaler distributes the products to a network of so-called Cash & Carry (C&C) locations, which act as local markets for florists.

The supply chain for the case is supply driven (Figure 6.1). Based on forecasts for demand coming from C&Cs, products are purchased from the auction and from growers directly. These products are put in a central stock. Based on forecasts for demand coming from florists, C&Cs order products from the central stock. These products are transported to the C&Cs and put in de-central stocks. Based on forecasts for demand coming from consumers, florists purchase products from the de-central stocks. The CODP is thus at the florist shops, where bouquets are made, customised to the consumers' requirements at the moment of purchase. As changes to the network are limited to the hub locations and as florists are located close to the C&Cs, it is agreed upon with sector partners that the scope for this study should cover the supply chain from grower to C&C. The products considered are a selection of the most sold cut flowers.

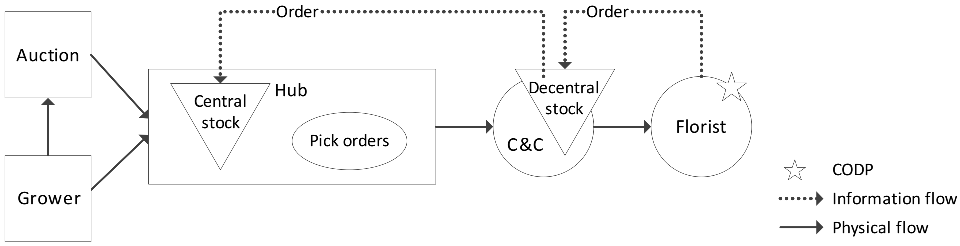


Figure 6.1: Current supply driven chain for cut flowers traded via a wholesaler

The quality of cut flowers is expressed in remaining vase life, i.e. the time flowers can be kept on the vase at room temperature (Tromp et al., 2012). Product quality decay is expressed as loss in vase life. For roses, the degree-days model (Tromp et al., 2012) can be used to determine vase life throughout a logistics chain. Flowers have an initial vase life v_0 when they are harvested at the grower. Loss in vase life Δv caused by a logistics operation is a function of the duration d (in days) of the operation and the temperature T under which it is executed: $\Delta v = (T - T_0)/(T_{ref} - T_0) * d$, where T_{ref} is room temperature and T_0 can be described as the preferred temperature for logistics operations. Then, remaining vase life is: $v = v_0 - \Delta v$.

In consultation with sector partners, and supported by technological research that analyses vase life for specific cut flowers under specific conditions, the remaining vase life is determined for the cut flowers considered in this case. It is assumed that the degree-days model, although specifically developed for roses, can be used as rough estimation for the remaining vase life of different cut flowers using different values for v_0, T_0 and $r := 1/(T_{ref} - T_0)$. Roses are then used as reference to categorize the different cut flowers and to determine parameter values for the defined categories: general flowers, for which decay is similar to roses; sensitive flowers, which have a shorter initial vase life than roses and which decay faster; tropical flowers, which have a shorter initial vase life than roses and a higher preferred temperature.

6.3.3 Scenarios for supply and demand driven chains

One of the key developments in the floricultural sector is the increasing market share of retail and e-tail at the cost of the market share of detail (De Keizer et al., 2015b). This means that supply chains are shifting from being supply driven to becoming demand driven. The defined scenarios therefore show a three-step transition from supply to demand driven chains (Figure 6.2). The transition implies a change in the logistics operations that are present in the supply chain as well as a change in the commercial operations. In supply driven chains (i.e. detail), flowers are for the largest part purchased

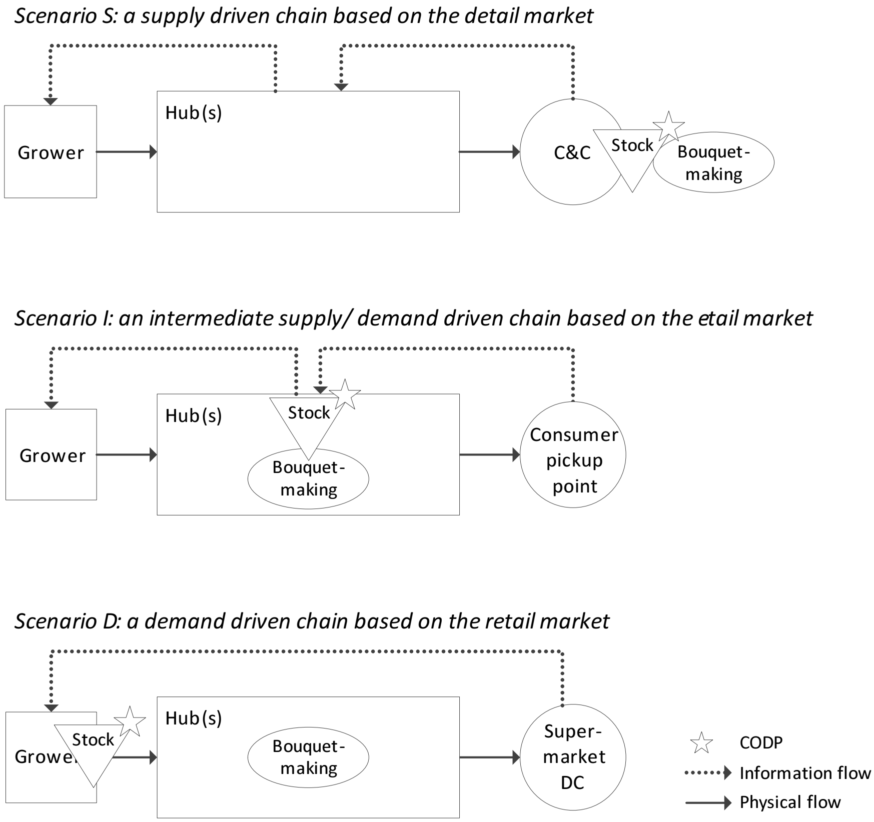


Figure 6.2: Different supply chains from supply to demand driven

at flower auctions. The price mechanism of a flower auction is based on demand and supply per quality category, which induces a price sensitivity to product quality. In demand driven chains (i.e. e-tail and retail), flowers are purchased by direct trade. This implies that (long-term) agreements are made in which a price is set and which can state a minimum quality that is to be guaranteed for the supplied products. The following scenarios are defined:

Base scenario B – This scenario is defined based on the current network and serves as reference. It considers a supply driven chain for the detail market in which the CODP is at the customer locations. It furthermore considers the current locations in the network, which means that central stock of cut flowers is kept at a Dutch hub location and de-central stock is kept at customer locations in order to serve florists. Revenues earned at the customer locations depend on the vase life of the cut flowers delivered.

Scenario S – This scenario considers a supply driven chain based on the detail market similar to the base scenario. However, instead of using the current hub location, optimal hub locations are searched for (potential hub locations are selected in between current grower and customer locations and products can go through one or more hub locations). It assumes that de-central stock of cut flowers is kept at customer locations in order to serve florists. It is a fresh product chain with the CODP at the customer locations. It is a scenario focused on large order volumes shipped with a low frequency to a limited number of customer locations. In addition, revenues earned at the customer locations depend on the vase life of the cut flowers delivered.

Scenario I - This scenario is based on the e-tail market. It considers a more demand driven chain in which bouquets must be distributed to customer locations in order to serve web-shops. It is a processed product chain with the CODP at a hub location. Different from scenario S, bouquet-making processes for mixed and mono bouquets need to be allocated in the supply chain. Furthermore, the customers require to be delivered within a short lead time and therefore stock should be kept at a hub location close enough to the customer locations. As a consequence, not only optimal hub locations but also optimal stock and process configurations are searched for. It is a scenario focused on small order volumes shipped with a high frequency to a large number of customer locations. It is the only scenario in which the customer locations are adjusted, to represent the increased number of customers. Each customer location from the base scenario is converted into eight new customer locations where the new coordinates are randomly deviated from the original coordinates. Furthermore, the customers require a minimum vase life of the bouquets delivered and only pay a set price if this requirement is satisfied.

Scenario D - This scenario considers a demand driven chain based on the retail market. This implies that bouquets must be distributed to customer locations in order to serve supermarkets. It is a processed product chain with the CODP at the grower locations. Similar to scenario I, optimal hub locations and optimal process configurations are searched for. However, different from scenario I, customers order well in advance and therefore stock can be moved upstream to the grower locations. It is a scenario focused on small order volumes shipped with a high frequency to a limited number of customer locations. Similar to scenario I, the customers require a minimum vase life of the bouquets delivered and only pay a set price if this requirement is satisfied.

Product perishability influences the network design and CODP allocation. To be able to analyse the influence of perishability on the configuration of logistics networks when shifting from a supply driven chain to a demand driven chain, two sub scenarios for scenarios S, I and D are defined, which differ in whether or not perishability is taken into account when the logistics network is configured.

The following sub scenarios are defined:

Sub scenario NoVL - This scenario resembles the common approach to network configuration. This entails that no loss in vase life is assumed when configuring the logistics network and allocating processes and stocks. The resulting logistics network is subsequently evaluated under real life conditions as they occur in the cut flower supply chain. These conditions imply that products are transported and handled under average conditions and the average temperature is not necessarily the temperature that is preferred for a specific product. Furthermore, there is some variability in the control of temperatures.

Sub scenario VL - In this scenario, an estimation of vase life losses and variability in vase life losses is already taken into account when configuring the logistics network and allocating processes and stocks. The resulting logistics network is subsequently evaluated under real life conditions (same as for scenario NoVL) to determine vase life losses more accurately.

An overview of all scenarios is given in Table 6.1.

Table 6.1: Scenario overview

ID	Main scenario factors				Sub scenario factor
	Number of customers	Order volume	Lead time	Revenue[a]	Perishability taken into account when network is configured[b]
B	Limited	High	None	Fixed	n.a.
S-NoVL	Limited	High	None	Sensitive	No
S-VL	Limited	High	None	Sensitive	Variability
I-NoVL	Large	Small	Short	Minimum	No
I-VL	Large	Small	Short	Minimum	Variability
D-NoVL	Limited	Small	Long	Minimum	No
D-VL	Limited	Small	Long	Minimum	Variability

[a] Sensitive: prices are sensitive to vase life; Minimum: fixed price for minimum vase life
[b] No: no vase life loss (no perishability); Variability: vase life loss including variability

6.4 Model formulation

A modelling approach is developed that can determine an optimal logistics network and evaluate the logistics network for a scenario. In Chapter 5, an optimisation model has been developed for designing a logistics network and allocating CODPs while taking into account product perishability. This model is used in this chapter to determine the optimal network configuration for a scenario at an aggregate level and to determine the costs of the network. Then, a simulation model is developed for evaluating the network configuration at a refined level and for determining network performance with respect to responsiveness and product quality. Due to the aggregation in the optimisation model, the detail in the simulation model results in a more accurate evaluation of the performance of the network. The evaluation might furthermore show that, although the network configuration is feasible at an aggregate level, it is actually infeasible at a detailed level due to too long lead times or too low vase life of products delivered at the customer locations. To improve the network configuration, a Hybrid Optimisation and Simulation (HOS) approach is developed, similar to De Keizer et al. (2015a), which uses the output from the simulation model to improve the parameters in the optimisation model.

6.4.1 Optimisation model

The optimisation model is a Mixed Integer Linear Programming (MILP) model, for which a detailed description is given in the appendix. The basis is a hub location model with a profit objective, where profits equal revenues minus fixed location costs and variable transport costs.

For scenarios I and D, the model has to be extended to also incorporate CODP allocation. First, process allocation decisions are added to the model. These determine at which hubs bouquets should be made. Fixed costs for installing a process and variable costs for processing are included in the objective function. Second, stock allocation decisions are added to the model. These determine which hubs are designated as strategic stock points from which either cut flowers or bouquets are directly available, and from where customer orders will be fulfilled (i.e. the CODP). The lead time from the stock allocation to the customer then consists of transport time and, if cut flowers are stored, processing time. For each customer and product, it is determined which stock allocations can meet the required lead time and the model has to select one of these feasible stock allocations. Fixed costs for installing a storage room and variable costs for storing products are included in the objective function.

For sub scenario VL, the model incorporates product quality decay. While products move through the network, vase life decreases in time and due to specific temperatures during transport, storage or processing. This loss in vase life is discretised by defining vase life categories in the model, where the number and width of vase life categories determine the accuracy with which loss in vase life is incorporated. Each product starts in a given vase life category at the grower and for each logistics operation it shifts to an equal or lower vase life category. Using the degree-days model, the operations characteristics and the decay rate of the product define the mean drop in categories for a product. When a bouquet is made, the vase life category for the bouquet is equal to the lowest category among the cut flowers used minus the drop in categories due to processing. For transport and storage, variability in loss of vase life is modelled by defining a distribution around the mean drop in categories. The vase life categories are furthermore used to determine revenues. In scenario S, revenues consist of the number of cut flowers delivered at a customer location multiplied by a price that depends on the vase life category for the flowers when delivered at the customer location. In scenarios I and D, revenues consist of the number of bouquets delivered at a customer location multiplied by a fixed price, but only if the vase life category for the bouquets is above a minimum category as required by the customer. Operations characteristics and product quality parameters are set based on feedback from sector partners. In sub scenario No-VL it is assumed that there is no product quality decay, which is modelled by defining one product quality category.

6.4.2 Simulation model

A Discrete Event Simulation (DES) model is developed for each scenario. The core of the simulation model, which is the same for all scenarios, is described and where needed, differences between scenarios are indicated. Using the framework of Robinson (2007), the simulation model is described in three parts: objective and scope, level of detail and data requirements.

Objective and scope

The objective is to evaluate networks, configured with the optimisation model, on responsiveness and vase life. Simulation will determine whether orders are delivered on time, in full and with the required vase life. Furthermore, the average delivery time, the average vase life and the amount of products spoiled throughout the chain will be determined. The scope is the same as for the optimisation model and covers the supply chain from growers via hubs to customers (C&Cs in the current network and scenario S, consumer pickup points in scenario I and supermarket DCs in scenario D). In the current network and scenario S, the hubs are stock locations. In scenarios I and D, the hubs can be stock as well as process locations. The frequencies of customer orders create a fixed weekly pattern. Therefore, the time horizon for the simulation is set at six weeks with a warmup period of one week. To get a statistically stable output, the number of replications is set at ten.

Level of detail

Cut flowers, bouquets and orders are the **entities** in the network. Cut flowers and bouquets have an attribute that registers the remaining vase life throughout the network using the degree-days model. Orders are used to steer the information flow and to

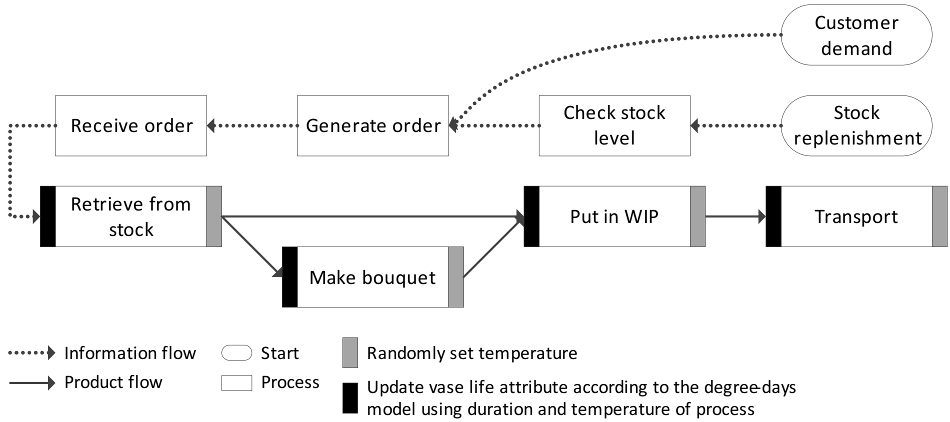


Figure 6.3: Process flow diagram of the DES model

decouple the part of the chain based on forecasts from the part of the chain based on customer orders.

The **activities** in the network are the growers, processes and customers. The growers supply cut flowers with a certain initial vase life. In scenarios B and C, the cut flowers are turned into bouquets by processes. A bill of materials denotes the types and quantities of cut flowers needed to produce one bouquet. The quality of a bouquet is as good as the worst flower in it. Therefore, the vase life of a bouquet is set at the lowest vase life of the cut flowers used, minus the loss in vase life due to processing. This loss in vase life is determined by the processing time and temperature that are set for the process. The cut flowers or bouquets are finally distributed to the customers based on orders. These orders are generated at given times and frequencies, where frequencies can vary over products and customers. In the current network and scenario S, orders state the demand quantities for cut flowers and are sent to the stock preceding the customer. In scenarios I and D, orders state demand quantities for bouquets and are sent to the stock that represents the CODP.

Work In Process inventories (WIPs) and stocks are the **queues** in the network. WIPs are used to coordinate the flows of entities between activities. Products are temporarily stored in these queues and are issued according to a First In First Out (FIFO) policy. Stocks are used to fulfill orders and are controlled using a base stock policy. This policy induces an order generation process, where orders are sent to upstream queues. Also for these queues, products are issued according to a FIFO policy. To prevent excess loss in vase life, a maximum time is set for products to be in stock and if this time is exceeded the products are discarded. When a product leaves a queue, a loss in vase life is accounted for based on the storage time and a temperature that is set for the queue.

Table 6.2: Inputs for simulation

	Deterministic input	Stochastic input
Grower	• Distance to queues (hubs)	• Initial vase life $\sim Beta(min_i, max_i)$
WIP	• Distance to activities (processes) and queues (hubs)	• Temperature $\sim N(\mu_w, \sigma_w)$
Stock	• Distance to activities (processes) and queues (hubs) • Stock policy parameters • Capacity • Maximum staytime	• Temperature $\sim N(\mu_h, \sigma_h)$
Process	• Bill of materials • Processing time • Schedule	• Temperature $\sim N(\mu_p, \sigma_p)$
Customer	• Distance to queues (hubs)	• Demand quantity $\sim N(\mu_c, \sigma_c)$
Plane	• Number available • Speed • Loading time	• Temperature $\sim N(\mu_{pl}, \sigma_{pl})$
Truck	• Number available • Speed • Loading time	• Temperature $\sim N(\mu_{tr}, \sigma_{tr})$

The **resources** in the network are planes and trucks. Planes are used to transport products from overseas growers, all other transport is done by trucks. The difference in the two resources is the speed. Speed and distance determine the duration of transport and, together with the temperature during transport, determine the loss in vase life for the products transported. As it should not be a bottleneck, resources are always available.

To illustrate the way the simulation runs, Figure 6.3 gives an overview of the **process flow**. Either a customer demand or a stock replenishment leads to the generation of an order. This order is forwarded in messages until it reaches the stock from which the order should be fulfilled. The needed products are retrieved from that stock and turned into bouquets if needed. The products are stored in a WIP until they are ready for transport to the location where the order came from. After storage, bouquet-making and transport, the vase life of the products is updated based on the process duration and temperature, which is randomly set.

Data requirements

Specifically to indicate how uncertainty is effectuated, the inputs for the simulation model are given in Table 6.2 and the outputs are given in Table 6.3. Input values are set based on feedback from sector partners.

Table 6.3: Outputs for simulation

Category	Output	Definition
Responsiveness	average delivery time	average over delivery times (i.e. time between ordering and delivering) for the products delivered to the customers
	% in full	number of customer orders for which all products are delivered at the same time at the customer location as percentage of total number of customer orders
	average lead time	average over lead times (from the stock allocation to the customer) for the products delivered to the customers
	% in time	number of products delivered within the required lead time as percentage of total number of products delivered at the customer locations
Product quality	average vase life	average over vase life for the products delivered to the customers
	% right vase life	number of products delivered with at least the minimum acceptable vase life as percentage of total number of products delivered at the customer locations

6.4.3 Interaction between optimisation and simulation

Use of the optimisation model for the simulation model and vice versa is given in pseudo-code in Algorithm 6.1. The optimal network configuration can turn out to be infeasible in the simulation due to lead time requirements or vase life requirements not being met. In case lead time requirements cannot be met, the infeasible stock allocations are eliminated in the optimisation model. In case vase life requirements cannot be met, the number of vase life categories is increased to increase the accuracy of the optimisation model with respect to vase life.

The optimisation model is implemented using IBM ILOG CPLEX Optimization Studio 12.6. The simulation model is implemented in FlexSim (6.0.2). The HOS approach is run on a laptop with a 2.40 GHz Intel core i5 and 4GB RAM (CPLEX uses up to 100% of CPU capacity, simulations in FlexSim can run only on one thread and use up to 25% of CPU capacity).

6.5 Results

The scenarios are compared to base scenario B with respect to network structure and performance. Subsequently, the logistics networks are ranked for different performance indicators. As different actors in the floricultural supply chain can have different performance objectives, the ranking is furthermore used to determine a suitable network in case of prioritised performance indicators.

Algorithm 6.1: Algorithm in pseudo-code

Algorithm: HOS approach

Result: Heuristically determines a network configuration that maximises profits and meets lead time and vase life requirements

Initialisation:

$stop = false$; $iter = 0$; $maxiter$ = maximum number of iterations; N = number of simulation runs;

$categories$ = number of vase life categories used in optimisation model;

α_{cp} = % of products p delivered to customer c within lead time at most equal to maximum required;

γ_{cp} = % of products p delivered to customer c with vase life at least equal to minimum required;

β_{cp} = service level of customer c for product p;

while *not stop* **do**

    Step 1: Run optimisation model;

    Step 2:

    a: Configure simulation model with solution from optimisation model;

    b: Run simulation model N times; Provides α_{cp} and γ_{cp};

    c: Check whether delivered products meet service level:

        if $(\alpha_{cp} >= \beta_{cp})$ & $(\gamma_{cp} >= \beta_{cp})$ $\forall$ *customer c, product p* **then**

            Required service levels are reached;

            $stop = true$;

        else

            foreach *customer c, product p* **do**

                if $\alpha_{cp} < \beta_{cp}$ **then**

                    Remove selected stock allocation for customer c and product p from optimisation model;

                end

                if $\gamma_{cp} < \beta_{cp}$ **then**

                    Set $categories = categories + 10$;

                end

            end

        end

    $iter = iter + 1$;

    if $iter > maxiter$ **then**

        $stop = true$;

end

Return best solution

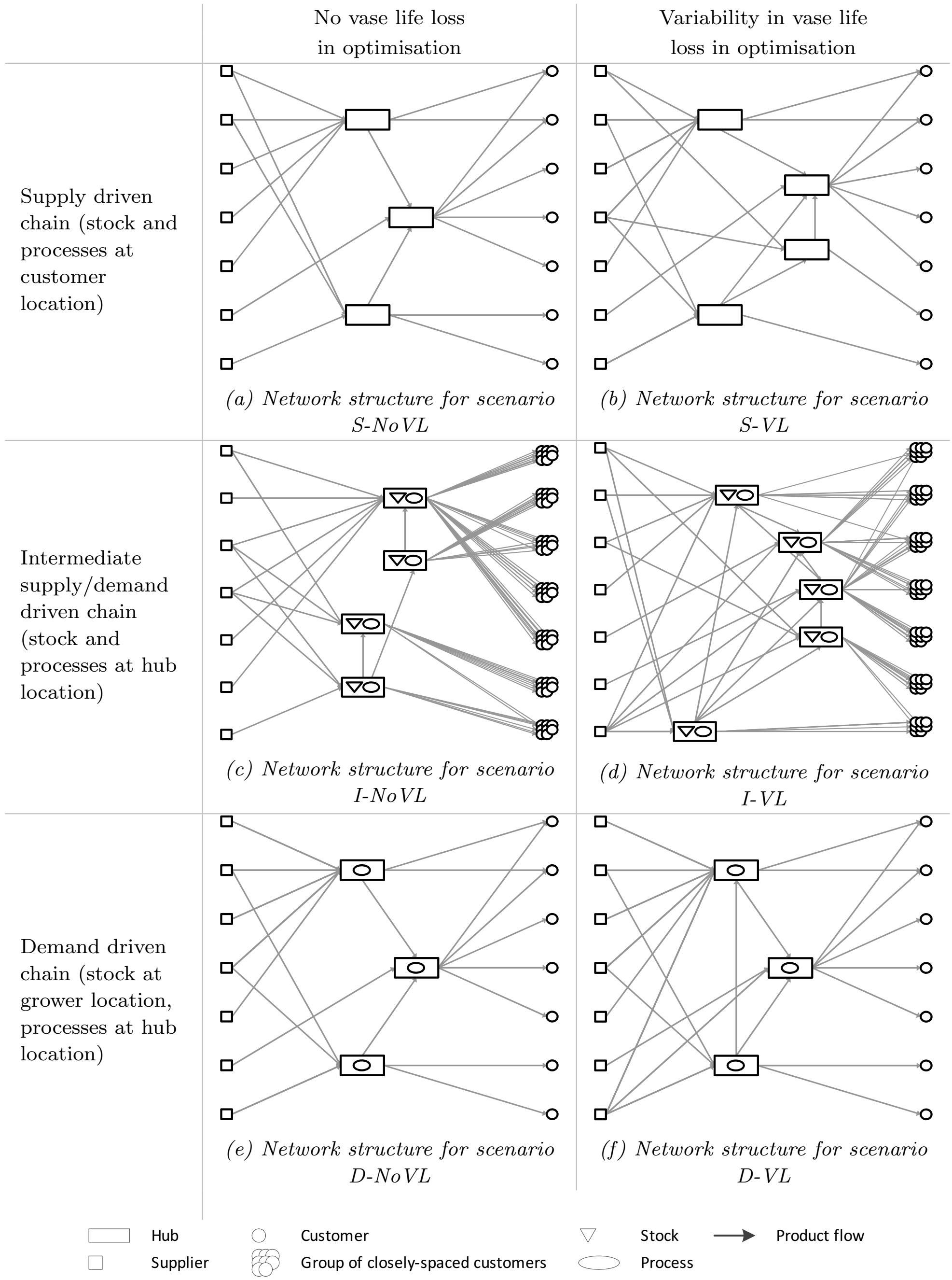
6.5.1 Logistics networks and performance for scenarios

Table 6.4: Performance of networks (normalised to base scenario performance)

	Optimisation KPIs			Simulation KPIs			
Scenario	Total costs	Facility costs	Transport costs	Average delivery time	% in full	Average vase life	% right quality
B	100	**100**	100	100	**100**	100	100
S-NoVL	**97.7**	300	90.1	52.5	98.1	101.0	99.8
S-VL	98.0	400	**89.6**	60.0	96.2	**101.1**	99.9
I-NoVL	112.9	400	92.2	39.8	99.6	75.4	99.2
I-VL	113.5	500	91.8	**35.5**	99.9	74.5	**101.5**
D-NoVL	99.9	300	92.6	225.1	99.5	75.0	96.8
D-VL	100.2	300	93.6	218.5	99.5	75.5	101.2

Note: Bold numbers indicate best performance for a KPI

For **base scenario B**, the logistics network is not optimised, but is given by the current centralised network. Hence, it is a network in which each supplier delivers the goods to a central hub after which goods are sorted and combined for distribution to customers. The network contains one hub location and the CODP is at the florists. This network is taken as the benchmark and key performance indicators (KPIs) for costs, responsiveness (average delivery time and percentage of orders delivered in full) and product quality (average vase life and percentage of orders delivered with acceptable quality) are set to 100 (Table 6.4). Results show that the base scenario has the best network with respect to facility costs and delivering orders in full. The low facility costs can be explained by the fact that the current network consists of only one hub. This also implies that there is no consolidation of flows between hubs and no corresponding efficiency advantage, resulting in the highest transport costs for the base scenario. It furthermore implies that central stock, to replenish the de-central stocks at the customer locations, is kept at one hub, which benefits risk pooling. Risk pooling decreases the probability of stock-outs and ensures that enough products are present to fulfill customer orders.



(a) Network structure for scenario S-NoVL

(b) Network structure for scenario S-VL

(c) Network structure for scenario I-NoVL

(d) Network structure for scenario I-VL

(e) Network structure for scenario D-NoVL

(f) Network structure for scenario D-VL

Figure 6.4: Network structures for different scenarios

For **scenarios S-NoVL and S-VL**, optimisation of the logistics network results in a decentralised network, i.e. a network in which each supplier delivers the goods to a central collection hub, after which goods are sorted, consolidated and transported to a distribution hub, where goods are resorted, recombined and distributed to customers. Similar to the base scenario, the CODP is at the florists (Figure 6.4a and 6.4b). Consolidation of product flows between hubs increases the efficiency of the transport and therefore transport between hubs has lower transport costs. This causes the total costs for the scenarios to be lower than for the current network. Costs for scenario S-VL are a bit higher than for S-NoVL, but this can be compensated by a higher revenue due to a higher vase life of the products delivered to the customers. This particularly holds for the most expensive products. In scenario S-VL, more hubs are opened to create more direct transport routes for these products, which decreases the transport time from grower to customer and with that the loss in vase life. The vase life of low price products decreases in scenario S-VL, which causes the average vase life for scenarios S-NoVL and S-VL to be practically the same. Due to the level of decentralisation compared to the current network, products can be delivered faster. Although the network for scenario S-VL is even more decentralised than for scenario S-NoVL, the increase in stock points decreases the pooling benefits and increases the probability of stock-outs. The stock-outs are a consequence of uncertain demand, but also of uncertain stock levels as products can get spoiled during storage. The result is an increase in the orders that cannot be delivered in full and with that an increase in average delivery time.

Also decentralised networks are provided when the logistics networks are optimised for **scenarios I-NoVL and I-VL**, but in these scenarios the CODP is at a hub (Figure 6.4c and 6.4d). For most products and customers, the CODP is a flower stock point at the closest hub. In scenario I-NoVL, bouquets have to be stored for 7% of the customers to be able to deliver on time. Similar to scenarios S, more hubs are opened in scenario I-VL than in scenario I-NoVL to decrease transport times and in turn increase the vase life of products delivered to customers. As a result of decreasing transport times, bouquets have to be stored for only 3.5% of the customers to be able to deliver on time in scenario I-VL. As a result of increasing vase life, the percentage of cut flowers delivered with at least the required vase life is higher in scenario I-VL than in scenario I-NoVL. Growers furthermore distribute their products to different hubs in scenario I-VL, which benefits customers for which the requirements could not be met in scenario I-NoVL, but it comes at the cost of customers for which the service levels were met beyond what was required. This even causes the average vase life to decrease instead of increase in scenario I-VL. Due to the lead time requirements, the average delivery time is the shortest for these scenarios. In combination with the product quality requirements, the number of orders that is delivered on time also improves from 95.3% in scenario I-NoVL to 97.7%

in scenario I-VL. Overall, the network for scenario I-VL is the most reliable. The costs of the networks in scenario I are the highest due to the costs for stock and the transport costs of bouquets.

Compared to the current network, logistics networks that result from the optimisation for **scenarios D-NoVL and D-VL**, can be depicted as decentralised, with the CODP at the growers (Figure 6.4e and 6.4f). The costs of these networks are comparable to the current network as the decrease in transport costs due to consolidation of flows between hubs equals the additional process costs. To decrease the time spent in the network and subsequently the loss in vase life, more products are transported from growers to customers passing only one hub in scenario D-VL. This causes the network in scenario D-VL to be more centralised than the network in scenario D-NoVL. For scenarios D-NoVL and D-VL, the delivery time also incorporates the time from the grower to the hubs and the processing time. The average delivery time is therefore substantially higher than for the current network. Due to the increase in product flows passing only one hub in scenario D-VL, the percentage of cut flowers delivered with at least the required vase life is higher than in scenario D-NoVL. Similar to scenarios I, growers distribute their products to different hubs in scenario D-VL, which benefits customers for which the requirements could not be met in scenario D-NoVL and harms customers for which the service levels were met beyond what was required. However, in these scenarios the consequences are less severe and the average vase life increases slightly in scenario D-VL.

6.5.2 Ranking of logistics networks based on performance

In Table 6.5 the scenarios are summarised and ranked based on the performance of the logistics networks. Each row shows the ranking for one performance indicator. Each column is based on a scenario, ordered from most supply driven to most demand driven: current network, S-VL, I-NoVL, I-VL, D-VL, D-NoVL (to show the influence of postponement, for the columns I-NoVL and I-VL customers are compared for which bouquets were stored in I-NoVL and for which flowers were stored in I-VL). The basis of the ranking is similar to Chopra & Meindl (2013), who compare line networks with centralised networks including different stock allocations. In this chapter, this is extended to the comparison of centralised with decentralised networks including different stock as well as process allocations, i.e. level of postponement and CODP allocation. Furthermore, next to costs and responsiveness, the networks are ranked on product quality.

Table 6.5: Typology and ranking of logistics networks for perishable products[a]

Performance category and indicator	Network typology					
	Storage at customer		Storage at hub		Storage at grower	
	Central	De-central	De-central		Central	De-central
	Post-ponement	Post-ponement	No post-ponement	Post-ponement	Post-ponement	Post-ponement
	Base	S-VL	I-NoVL	I-VL	D-VL	D-NoVL
Efficiency						
Facility costs	1	4	4	6	2	2
Inventory costs	5	6	4	3	1	1
Transport costs	6	1	3	2	4	3
Responsiveness						
In full	1	6	2	1	2	2
Lead time[b]	1	1	4	3	5	6
Product quality						
Average quality	2	1	3	4	3	4
Right quality	3	3	4	1	1	6

[a] Rank 1 corresponds to the highest performance and 6 to the lowest; when the difference in performance (Table 6.4) is less than 0.5%, corresponding scenarios are ranked the same; when the difference in performance is less than 1%, the difference in ranks is at most 1

[b] For scenarios with the CODP at the customer location, average lead time is zero; for scenarios with the CODP at a hub or grower location, lead time is equal to delivery time

Interaction between the number of hubs and performance

Chopra & Meindl (2013) state that fixed costs for hubs and stocks increase with the number of hubs and variable transport costs decrease with the number of hubs. Total costs first decrease when the number of hubs increases. This effect is also visible in the results in this chapter when comparing central and decentral networks (see the first three rows for column one versus column two and column five versus column six in Table 6.5). Furthermore, Chopra & Meindl (2013) state that lead time decreases when the number of hubs increases, which is supported by the results in this chapter (see the third and fourth columns and fourth row in Table 6.5).

In the papers of Rijpkema et al. (2014) and Van der Vorst et al. (2009), costs increase in order to improve product quality. Although this is the case in most scenarios in this study as well, it is also shown that both performance indicators can be improved at the same time (see the first two columns in Table 6.5). Increasing the number of hubs decreases costs, while at a certain point it creates more direct transport routes, which decreases transport times and increases product quality. Therefore, decentralisation can improve both costs and product quality.

Interaction between postponement and performance

In general, increasing the level of postponement decreases inventory costs (Forza et al., 2008). Decreasing the level of postponement can decrease lead time, even when the number of hubs decreases (see the fourth row for the third and fourth column in Table 6.5). Similar to Sharda & Akiya (2012), increasing the level of postponement decreases on-time delivery.

When the level of postponement is decreased (see columns three and four in Table 6.5), cut flowers are turned into bouquets and customised before they are stored. The customisation reduces the potential destinations for the products and decreases the number of customers per stock point. Next to the increase in stock-outs, this also increases the time products are stored before they are ordered. The increased storage time decreases product quality and makes it harder to deliver the right quality to the customers.

Interaction between CODPs and performance

In general, moving the CODP downstream in the supply chain (reading from right to left in Table 6.5) creates a more efficient supply chain and moving the CODP upstream in the supply chain (reading from left to right in Table 6.5) creates a more responsive supply chain (e.g. Olhager, 2010; Cirullies et al., 2011). This does not directly hold in this study. Instead of a decrease, an increase or no change is observed in the average ranking for the cost indicators when the CODP is moved downstream. This might be due to the fact that the networks are also optimized and an upstream CODP allows for more flexibility in the network and thus more options to configure the network. The average ranking for the responsiveness indicators does not show a clear increase or decrease when the CODP is moved upstream. The influence of the CODP on the responsiveness of the logistics network depends on the selected indicators.

Van der Vorst (2000) states that moving the CODP downstream decreases lead time, requires high delivery reliability and controls supply uncertainty, while moving the CODP upstream controls perishability of the products. The results in this chapter show that this trade-off not only depends on the position of the CODP but on the network structure as well. For example, when the CODP is moved downstream to be able to deliver faster, hubs and stocks need to be closer to customers and therefore more hubs are needed and more stocks are allocated (see columns two and four in Table 6.5). The increase in stock points decreases the level of risk pooling, which increases the risk of obsolescence and products getting spoiled before they are ordered. Spoilage leads to more stock-outs and in turn decreases instead of increases delivery reliability.

In summary, within the scope of the supply chain up to the customer locations, decentralising the network and moving the CODP downstream towards the customers improves the performance from a cost perspective. From a responsiveness perspective, decentralising the network and moving the CODP downstream towards the customers improves the performance with respect to lead time and on time delivery. However, centralising the network improves the performance with respect to delivering orders in full. Vase life of the products delivered to the customers can be improved by creating a more dense network or by centralising the network. The CODP should be moved to both ends of the supply chain; at the customers when flowers are demanded and at the growers when bouquets are demanded.

6.5.3 Selection of a logistics network for supply chain actors

Different actors in the floricultural supply chain network have different objectives. Product quality is seen as a precondition to do business. As quality is initially determined at the time of harvesting, it is particularly an important criterion for growers. Furthermore, there is a trade-off between efficiency and responsiveness. Growers and traders often outsource logistics operations to Logistics Service Providers (LSPs). As a result, growers and traders specify conditions with respect to, for example, lead times. LSPs then aim to execute the assigned tasks at the lowest costs given the conditions. In consultation with sector partners, this is translated in prioritised multi-criteria objectives:

- For growers, product quality is given the highest priority, followed by responsiveness and efficiency respectively.
- For traders, responsiveness is given the highest priority, followed by efficiency and product quality respectively.
- For LSPs, efficiency is given the highest priority, followed by responsiveness and product quality respectively.

The performance ranking (Table 6.5) indicates the performance of logistics networks for individual criteria. To determine the performance of logistics networks for the multi-criteria objectives, the ranking is used in an Analytical Hierarchy Process (AHP) (Saaty, 1990). First, the hierarchy of the problem is set:

- The aim is to find the best logistics network, therefore, the top level in the hierarchy is the overall performance of a logistics network.
- Each performance indicator from the ranking contributes to the overall performance, therefore, the second level in the hierarchy contains the indicators.
- The logistics networks that are ranked are the candidates and constitute the third level in the hierarchy.

At the second level, performance indicators are pairwise compared to determine the relative importance of the indicators with respect to the overall performance. It is assumed that there is no difference in importance for indicators within a performance category (efficiency, responsiveness, product quality). The relative importance of

Table 6.6: Optimal logistics networks for different floricultural supply chain actors

Actor	Relative importance			Network	Multi-criteria decision	
	Efficiency	Responsiveness	Product quality		Global priority	Optimal network
Grower	0.12	0.19	0.69	Base	0.180	Storage at customers in de-central network with postponement
				S-VL	**0.225**	
				I-NoVL	0.104	
				I-VL	0.196	
				D-VL	0.199	
				D-NoVL	0.095	
Trader	0.25	0.68	0.07	**Base**	**0.260**	Storage at customers in central network with postponement
				S-VL	0.192	
				I-NoVL	0.108	
				I-VL	0.176	
				D-VL	0.137	
				D-NoVL	0.125	
LSP	0.80	0.14	0.06	Base	0.186	Storage at growers in central network with postponement
				S-VL	0.185	
				I-NoVL	0.104	
				I-VL	0.138	
				D-VL	**0.195**	
				D-NoVL	0.193	

indicators from different performance categories is based on the objectives ordering for an actor. Using the scale given in Saaty (1990), objective 1 is 5 times more important than objective 2 and 7 times more important than objective 3, objective 2 is 3 times more important than objective 3.

At the third level, logistics networks are pairwise compared to determine the relative importance of the networks with respect to each performance indicator from the second level. It is assumed that the relative importance of a network X over a network Y is given by the relative rank of network X compared to network Y. For example, if network X has rank 4 for a performance indicator and network Y has rank 2, than the relative importance of network X is 4/2.

The pairwise comparisons are used to determine local priorities, which are aggregated to global priorities using weighted sums. The logistics network with the highest global priority is then depicted as the best network for the multi-criteria objective. Table 6.6 shows the results for growers, traders and LSPs respectively.

For growers, the main objective is product quality and this causes logistics networks from the VL scenarios to be preferred over logistics networks from the NoVL scenarios. Although the supply driven network is appointed as the best network, the logistics networks from the VL scenarios do not differ much in overall performance. When product quality is the least important objective, the differences between logistics networks from VL and NoVL scenarios are generally small. The results show that when product quality is a key objective, optimisation of the network configuration should take into account perishability. When product quality is s secondary objective, also the incorporation of perishability in the optimisation of the network configuration is of secondary importance.

For traders, the main objective is responsiveness and this causes a clear preference for the current network. When responsiveness would be more related to flexibility than to fast delivery and delivery in full, the priority of the demand driven network would increase.

For LSPs, who have costs as the main objective, the differences in performance of the logistics networks are the smallest. It shows that responsiveness and product quality objectives particularly determine the best network.

6.6 Discussion and conclusion

In this chapter, a network characterisation is developed for supply driven and demand driven supply chains for perishable products. Based on literature review, an initial network characterisation is developed with respect to hub location and CODP allocation, which does not take into account perishability of products. Furthermore, the interplay of product perishability and hub location and the interplay of product perishability and CODP allocation are analysed. Based on a case from the Dutch floricultural sector, a network characterisation is developed that does explicitly take into account perishability of products. Different scenarios are defined to represent supply driven chains, intermediate supply/demand driven chains and demand driven chains. For these scenarios the optimal network, i.e. hub locations and process and stock allocations, and associated costs are determined using MILP. The performance of the network with respect to responsiveness and product quality is evaluated using simulation. If the performance does not satisfy the requirements, the simulation results are used to update the optimisation model to improve the optimal network.

Results show that allocating the CODP given the existing locations ignores the CODP allocations that become feasible with new locations. Therefore, hub location and CODP allocation decisions should be optimised together. The performance of the optimal logistics network is a trade-off especially between responsiveness and product quality. The current logistics network for the floricultural sector performs well when it comes to delivering fast and in full, however, when product quality or costs are important a more elaborate hub network is needed. As different actors in the supply chain have different objectives and different objectives result in different networks, there is no shared optimal hub network. The crucial parts in the network are the stock points and close attention should be paid to the stock policies so as to limit the risk of spoilage and consequent stock-outs.

Although the studied case is a specific example, the scenario approach gives insight in the mechanisms in such a way that it can be used for other supply chains as well. The performance ranking points out the network characteristics that are advantageous for perishable products and network characteristics that are disadvantageous. More specifically, when the characteristics of a particular supply chain are analysed and compared with the different scenarios, the performance ranking in this chapter can give support for the type of network that is needed. To find the actual optimal network configuration, a detailed analysis will be needed for each case individually. The scenario approach also justifies the results, although a sensitivity analysis could strengthen the validity of the ranking.

The results from the case study show the added value of including product quality decay in logistics network configuration for cut flower supply chains. In future research, similar case studies for different sectors could be conducted to further generalise the insights in the influence of product quality decay on integrated hub location and CODP allocation decisions. Furthermore, as stock points are shown to be a crucial factor in the network configuration, future research could focus on the integrated optimisation of stock policy decisions in addition to the hub location and CODP allocation decisions. It is also shown that different objectives result in different optimal logistics networks. Future research could then focus on multi-objective optimisation.

Appendix C: Optimisation model

The MILP models developed for the different scenarios are described in this appendix. The most basic model, for scenario S, is first described. Then, the extended model with process allocations, for scenario D, is described. Finally, the extended model with stock allocations, for scenario I, is described.

Sets, variables and parameters:

Sets:

G	set of growers
C	set of customers
H	set of hubs
L	$= G \cup C \cup H$; set of locations
F	set of cut flowers
B	set of bouquets
P	$= F \cup B$; set of products
F_b	$\subset F$; cut flowers needed to produce bouquet b
$\overline{B}_f$	$\subset B$; bouquets in which cut flower f is used
$\{1, \ldots, V\}$	set of product quality categories, V is the highest category
$\{1, \ldots, N\}$	set of intervals in piecewise linear approximation of safety stock costs

Variables:

$Y_h \in \{0, 1\}$	hub h is open or not
$YP_h \in \{0, 1\}$	process is allocated to hub h or not
$YSF_h \in \{0, 1\}$	stock of cut flowers is allocated to hub h or not
$YSB_h \in \{0, 1\}$	stock of bouquets is allocated to hub h or not
$YSSF_{hn} \in \{0, 1\}$	demand variance of stored cut flowers at hub h falls in interval n or not
$YSSB_{hn} \in \{0, 1\}$	demand variance of stored bouquets at hub h falls in interval n or not
$X_{ijpv} \geq 0$	quantity of product p in quality category v at location i transported to location j upstream of the CODP
$X^*_{ijpv} \geq 0$	quantity of product p in quality category v at location i transported to location j downstream of the CODP
$XS_{hpv} \geq 0$	quantity of product p with quality category v put in stock at hub h
$XS^*_{hpvcb} \geq 0$	quantity of product p in quality category v retrieved from stock at hub h to be delivered as bouquet b to customer c
$XSSF^*_{hn} \geq 0$	demand variance of stored cut flowers at hub h in interval n

$XSSB^*_{hn} \geq 0$	demand variance of bouquets at hub h in interval n
$XPI_{hfbuv} \geq 0$	quantity of cut flower f in quality category u used to produce bouquet b in quality category v at hub h upstream of the CODP
$XPI^*_{hfbuv} \geq 0$	quantity of cut flower f in quality category u used to produce bouquet b in quality category v at hub h downstream of the CODP
$XPO_{hbv} \geq 0$	quantity of bouquet b in quality category v produced at hub h upstream of the CODP
$XPO^*_{hpv} \geq 0$	quantity of bouquet b in quality category v produced at hub h downstream of the CODP

Parameters:

ur_{cb}	unit revenue for delivering bouquet b to customer c
ur_{cfv}	unit revenue for delivering cut flower f to customer c in quality category v
fc_h	fixed annual costs for opening hub h
fcp_h	fixed annual costs for allocating process to hub h
$fcsf_h$	fixed annual costs for allocating stock of cut flowers at hub h
$fcsb_h$	fixed annual costs for allocating stock of bouquets at hub h
$ucssf_{hn}$	unit annual cost factor for demand variance of stored cut flowers at hub h within interval n
$ucssb_{hn}$	unit annual cost factor for demand variance of stored bouquets at hub h within interval n
uc_{ijp}	unit transport costs of product p from origin i to destination j
ucp_{hb}	unit production costs of bouquet b at hub h
ucs_{hp}	unit storage costs of product p at hub h
sup_{gfv}	yearly supply of cut flower f in quality category v by grower g
dem_{cp}	yearly demand of product p by customer c
sb^2_{cb}	daily demand variance of bouquet b demanded by customer c
sf^2_{fcb}	demand variance of stored cut flower f resulting from daily demand variance of bouquet b demanded by customer c
v_{cb}	minimum quality category demanded for bouquet b by customer c
lt_{hpcb}	feasibility of stock allocation: $= \begin{cases} 1 & \text{if lead time for bouquet } b \text{ demanded by customer } c \text{ can be met by storing product } p \text{ at hub } h \\ 0 & \text{otherwise} \end{cases}$
m_{fb}	quantity of cut flower f in one bouquet b
mm_{fb}	fraction of cut flower f in one bouquet b
M	big number
upf_{hn}	upperbound of interval n for demand variance of cut flowers at hub h

upb_{hn}	upperbound of interval n for demand variance of bouquets at hub h
c_{ijpuv}	fraction of flow of product p starting at location i in quality category u and arriving at location j in quality category v
cs_{hpuv}	fraction of flow of product p put in stock in quality category u and retrieved from stock in quality category v at hub h
cp_{hb}	decrease in quality category due to producing bouquet b at hub h

MILP for supply chains with the CODP at the customer

$$\max \quad \sum_{c\in C}\sum_{f\in F}\sum_{v=1}^{V} ur_{cfv} \sum_{h\in H}\sum_{u=v}^{V} c_{hcfuv}X_{hcfu} - \sum_{h\in H} fc_h Y_h - \sum_{i\in L}\sum_{j\in L}\sum_{f\in F}\sum_{v=1}^{V} uc_{ijf}X_{ijfv} \tag{6.1}$$

$$\sum_{h\in H} X_{ghfv} \leq sup_{gfv} \qquad \forall g\in G, f\in F, v\in\{1,\ldots,V\} \tag{6.2}$$

$$\sum_{h\in H}\sum_{v=1}^{V}\sum_{u=v}^{V} c_{hcfuv}X_{hcfu} = dem_{cf} \qquad \forall c\in C, f\in F \tag{6.3}$$

$$\sum_{i\in G\cup H\setminus h}\sum_{u=v}^{V} c_{ihfuv}X_{ihfu} = \sum_{i\in H\setminus h\cup C} X_{hifv} \qquad \forall h\in H, f\in F, v\in\{1,\ldots,V\} \tag{6.4}$$

$$\sum_{f\in F}\sum_{v=1}^{V}\sum_{i\in H\setminus h\cup C} X_{hifv} \leq M\cdot Y_h \qquad \forall h\in H \tag{6.5}$$

The objective (6.1) is to maximise profits. Profits equal returns from customers minus fixed location costs and transport costs. Equation (6.2) and (6.3) represent supply and demand balance constraints. The demand balances take into account that vase life for a product at the hub can be higher ($u \in V_w^+$) than at the customer due to transportation. Equation (6.4) ensures that hub inflows and outflows are balanced. Equation 6.5) ensures that flows can only exist if hubs are open or processes allocated.

MILP for supply chains with the CODP at the grower

$$\max \quad \sum_{c\in C}\sum_{b\in B} ur_{cb} \sum_{h\in H}\sum_{v=v_{cb}}^{V}\sum_{u=v}^{V} c_{hcbuv}X_{hcbu} - \sum_{h\in H} fc_h Y_h - \sum_{h\in H} fcp_h YP_h - \sum_{i\in L}\sum_{j\in L}\sum_{p\in P}\sum_{v=1}^{V} uc_{ijp}X_{ijpv} - \sum_{h\in H}\sum_{b\in B}\sum_{v=1}^{V} ucp_{hb}\cdot XPO_{hbv} \tag{6.6}$$

$$\sum_{h\in H} X_{ghfv} \leq sup_{gfv} \qquad \forall g \in G, f \in F, v \in \{1,\ldots,V\} \quad (6.7)$$

$$\sum_{h\in H} \sum_{v=v_{cb}}^{V} \sum_{u=v}^{V} c_{hcbuv} X_{hcbu} = dem_{cb} \qquad \forall c \in C, b \in B \quad (6.8)$$

$$\sum_{i\in G\cup H\setminus h} \sum_{u=v}^{V} c_{ihfuv} X_{ihfu} = \sum_{i\in H\setminus h} X_{hifv} + \sum_{b\in \overline{B}_f} \sum_{u=1}^{v-cp_{hb}} XPI_{hfbvu}$$
$$\forall h \in H, f \in F, v \in \{1,\ldots,V\} \quad (6.9)$$

$$\sum_{i\in H\setminus h} \sum_{u=v}^{V} c_{ihbuv} X_{ihbu} + XPO_{hbv} = \sum_{i\in H\setminus h\cup C} X_{hibv}$$
$$\forall h \in H, b \in B, v \in \{1,\ldots,V\} \quad (6.10)$$

$$XPO_{hbv} = \sum_{u=v+cp_{hb}}^{V} \frac{XPI_{hfbuv}}{m_{fb}} \qquad \forall h \in H, b \in B, f \in F_b, v \in \{1,\ldots,V\} \quad (6.11)$$

$$\sum_{f\in F} \sum_{v=1}^{V} \Big[\sum_{i\in H\setminus h} X_{hifv} + \sum_{b\in \overline{B}_f} \sum_{u=1}^{v-cp_{hb}} XPI_{hfbvu} \Big] \leq M \cdot Y_h \qquad \forall h \in H \quad (6.12)$$

$$\sum_{b\in B} \sum_{v=1}^{V} \Big[\sum_{i\in H\setminus h\cup C} X_{hibv} \Big] \leq M \cdot Y_h \qquad \forall h \in H \quad (6.13)$$

$$\sum_{b\in B} \sum_{v=1}^{V} XPO_{hbv} \leq M \cdot YP_h \qquad \forall h \in H \quad (6.14)$$

$$YP_h \leq Y_h \qquad \forall h \in H \quad (6.15)$$

The objective (6.6) is to maximise profits. Profits equal returns from customers minus fixed location and process costs, transport costs and variable process costs. Equation (6.7) and (6.8) represent supply and demand balance constraints. The demand balance takes into account that vase life for a product at the hub can be higher ($u \in V_w^+$) than at the customer due to transportation. Equation (6.9) and (6.10) represent balance constraints for hub inflows and outflows. Inflows and outflows for processes also have to be in balance, which is depicted in Equation (6.11). For processing it is taken into account that vase life before production can be different from vase life after production and that multiple products can be used to produce a bouquet. Equation 6.12) to (6.14) ensure that flows can only exist if hubs are open or processes allocated. Equation (6.15) ensures that processes can only be allocated if a hub is open.

MILP for supply chains with the CODP at a hub

$$\begin{aligned}
\max \quad & \sum_{c\in C}\sum_{b\in B} ur_{cb} \sum_{h\in H}\sum_{v=v_{cb}}^{V}\sum_{u=v}^{V} c_{hcbuv} X^*_{hcbu} - \sum_{h\in H} fc_h Y_h - \sum_{h\in H} fcp_h YP_h \\
& - \sum_{h\in H}\Big(fcsf_h YSF_h + fcsb_h YSB_h + \sum_{n=1}^{N}(ucssf_{hn} XSSF^*_{hn} + ucssb_{hn} XSSB^*_{hn})\Big) \\
& - \sum_{i\in L}\sum_{j\in L}\sum_{p\in P}\sum_{v=1}^{V} uc_{ijp}(X_{ijpv} + X^*_{ijpv}) - \sum_{h\in H}\sum_{b\in B}\sum_{v=1}^{V} ucp_{hb}\cdot(XPO_{hbv} + XPO^*_{hbv}) \\
& - \sum_{h\in H}\sum_{p\in P}\sum_{v=1}^{V} ucs_{hp} XS_{hpv}
\end{aligned} \tag{6.16}$$

$$\sum_{h\in H} X_{ghfv} \le sup_{gfv} \qquad \forall g\in G, f\in F, v\in\{1,\ldots,V\} \tag{6.17}$$

$$\sum_{h\in H}\sum_{v=v_{cb}}^{V}\sum_{u=v}^{V} c_{hcbuv} X^*_{hcbu} = dem_{cb} \qquad \forall c\in C, b\in B \tag{6.18}$$

$$\sum_{i\in G\cup H\setminus h}\sum_{u=v}^{V} c_{ihfuv} X_{ihfu} = \sum_{i\in H\setminus h} X_{hifv} + \sum_{b\in \overline{B}_f}\sum_{u=1}^{v-cp_{hb}} XPI_{hfbvu} + XS_{hfv} \qquad \forall h\in H, f\in F, v\in\{1,\ldots,V\} \tag{6.19}$$

$$\sum_{i\in H\setminus h}\sum_{u=v}^{V} c_{ihbuv} X_{ihbu} + XPO_{hbv} = \sum_{i\in H\setminus h} X_{hibv} + XS_{hbv} \qquad \forall h\in H, b\in B, v\in\{1,\ldots,V\} \tag{6.20}$$

$$\sum_{i\in H\setminus h}\sum_{u=v}^{V} c_{ihfuv} X^*_{ihfu} + \sum_{c\in C}\sum_{b\in \overline{B}_f} XS^*_{hfvcb} = \sum_{i\in H\setminus h} X^*_{hifv} + \sum_{b\in \overline{B}_f}\sum_{u=1}^{v-cp_{hb}} XPI^*_{hfbvu} \qquad \forall h\in H, f\in F, v\in\{1,\ldots,V\} \tag{6.21}$$

$$\sum_{i\in H\setminus h}\sum_{u=v}^{V} c_{ihbuv} X^*_{ihbu} + XPO^*_{hbv} + XS^*_{hbvcb} = \sum_{i\in H\setminus h\cup C} X^*_{hibv} \qquad \forall h\in H, b\in B, v\in\{1,\ldots,V\} \tag{6.22}$$

$$XPO_{hbv} = \sum_{u=v+cp_{hb}}^{V} \frac{XPI_{hfbuv}}{m_{fb}} \qquad \forall h\in H, b\in B, f\in F_b, v\in\{1,\ldots,V\} \tag{6.23}$$

$$XPO^*_{hbv} = \sum_{u=v+cp_{hb}}^{V} \frac{XPI^*_{hfbuv}}{m_{fb}} \qquad \forall h\in H, b\in B, f\in F_b, v\in\{1,\ldots,V\} \tag{6.24}$$

$$\sum_{c\in C}\sum_{b\in \overline{B}_f} XS^*_{hfvcb} = \sum_{u=v}^{V} cs_{hfuv}XS_{hfu} \qquad \forall h\in H, f\in F, v\in\{1,\dots,V\} \quad (6.25)$$

$$\sum_{c\in C} XS^*_{hbvcb} = \sum_{u=v}^{V} cs_{hbuv}XS_{hbu} \qquad \forall h\in H, b\in B, v\in\{1,\dots,V\} \quad (6.26)$$

$$\sum_{h\in H}\sum_{v=1}^{V}\Big[XS^*_{hbvcb} + \sum_{f\in F_b}(XS^*_{hfvcb}\cdot mm_{fb})\Big] = dem_{cb} \qquad \forall c\in C, b\in B \quad (6.27)$$

$$XS^*_{hpvcb} \le M\cdot lt_{hpcb}\sum_{n=1}^{N}(YSSF_{hn}+YSSB_{hn})$$
$$\forall c\in C, b\in B, p\in F_b\cup B, h\in H, v\in\{1,\dots,V\} \quad (6.28)$$

$$m_{f_2b}\sum_{v\in V} XS^*_{hf_1vcb} = m_{f_1b}\sum_{v\in V} XS^*_{hf_2vcb} \qquad \forall h\in H, c\in C, b\in B, f_1, f_2\in F_b \quad (6.29)$$

$$\sum_{c\in C}\sum_{b\in B}\sum_{f\in F_b} lt_{hfcb}sf^2_{fcb}\frac{\sum_{v=1}^{V} XS^*_{hfvcb}}{m_{fb}\cdot dem_{cb}} \le \sum_{n=1}^{N} XSSF^*_{hn} \qquad \forall h\in H \quad (6.30)$$

$$XSSF^*_{hn} \le upf_{hn}\cdot YSSF_{hn} \qquad \forall h\in H, n=1 \quad (6.31)$$

$$XSSF^*_{hn} \le (upf_{hn} - upf_{h(n-1)})\cdot YSSF_{hn} \qquad \forall h\in H, n\in\{1,\dots,N\} \quad (6.32)$$

$$\sum_{m<=n} XSSF^*_{hm} \ge upf_{hn}\cdot YSSF_{h(n+1)} \qquad \forall h\in H, n\in\{1,\dots,N-1\} \quad (6.33)$$

$$YSSF_{hn} \ge YSSF_{h(n+1)} \qquad \forall h\in H, n\in\{1,\dots,N-1\} \quad (6.34)$$

$$\sum_{c\in C}\sum_{b\in B} lt_{hbcb}sb^2_{cb}\sum_{v=1}^{V} XS^*_{hbvcb} \le \sum_{n=1}^{N} XSSB^*_{hn} \qquad \forall h\in H \quad (6.35)$$

$$XSSB^*_{hn} \le upb_{hn}\cdot YSSB_{hn} \qquad \forall h\in H, n=1 \quad (6.36)$$

$$XSSB^*_{hn} \le (upb_{hn} - upb_{h(n-1)})\cdot YSSB_{hn} \qquad \forall h\in H, n\in\{1,\dots,N\} \quad (6.37)$$

$$\sum_{m<=n} XSSB^*_{hm} \ge upb_{hn}\cdot YSSB_{h(n+1)} \qquad \forall h\in H, n\in\{1,\dots,N-1\} \quad (6.38)$$

$$YSSB_{hn} \ge YSSB_{h(n+1)} \qquad \forall h\in H, n\in\{1,\dots,N-1\} \quad (6.39)$$

$$\sum_{f\in F}\sum_{v=1}^{V}\Big[\sum_{i\in H\setminus h} X_{hifv} + \sum_{b\in \overline{B}_f}\sum_{u=1}^{v-cp_{hb}} XPI_{hfbvu} + XS_{hfv}\Big] \le M\cdot Y_h \qquad \forall h\in H \quad (6.40)$$

$$\sum_{b\in B}\sum_{v=1}^{V}\Big[\sum_{i\in H\setminus h} X_{hibv} + XS_{hbv}\Big] \le M\cdot Y_h \qquad \forall h\in H \quad (6.41)$$

$$\sum_{f\in F}\sum_{v=1}^{V}\Big[\sum_{i\in H\backslash h} X^*_{hifv} + \sum_{b\in \overline{B}_f}\sum_{u=1}^{v-cp_{hb}} XPI^*_{hfbvu}\Big] \leq M \cdot Y_h \qquad \forall h \in H \quad (6.42)$$

$$\sum_{b\in B}\sum_{v=1}^{V}\sum_{i\in H\backslash h\cup C} X^*_{hibv} \leq M \cdot Y_h \qquad \forall h \in H \quad (6.43)$$

$$\sum_{b\in B}\sum_{v=1}^{V}(XPO_{hbv} + XPO^*_{hbv}) \leq M \cdot YP_h \qquad \forall h \in H \quad (6.44)$$

$$YP_h \leq Y_h \qquad \forall h \in H \quad (6.45)$$

$$YSF_h \leq Y_h \qquad \forall h \in H \quad (6.46)$$

$$YSB_h \leq Y_h \qquad \forall h \in H \quad (6.47)$$

The objective (6.16) is to maximise profits. Profits equal returns from customers minus fixed location, process and stock costs, safety stock costs, transport costs and variable storage and process costs. Equation (6.17) and (6.18) represent supply and demand balance constraints. The demand balances take into account that vase life for a product at the hub can be higher ($u \in V_w^+$) than at the customer due to transportation. Equation (6.19) and (6.20) represent balance constraints for hub inflows and outflows upstream of the CODP. Equation (6.21) and (6.22) represent balance constraints for hub inflows and outflows downstream of the CODP. Inflows and outflows for processes and stocks also have to be in balance, which is depicted in Equation (6.23) to (6.26). For processing it is taken into account that vase life before production can be different from vase life after production and that multiple products can be used to produce a bouquet. For stock it is taken into account that vase life before storage can be different from vase life after storage. Customers require a guaranteed lead time and it is indicated which stock allocations can fulfill their requirements. Equation (6.27) and (6.28) ensure that enough products are stored to fulfill demand and only at stock points that are feasible and allocated. Furthermore, if stock is allocated for cut flowers, equation (6.29) ensures stocks for all inputs are allocated in balanced quantities. Equation (6.30) to (6.39) represent the piecewise linearisation of safety stocks. Equation (6.40) to (6.44) ensure that flows can only exist if hubs are open or processes allocated. Equation (6.45) and (6.47) ensure that processes and stocks can only be allocated if a hub is open.

Chapter 7

Conclusions and general discussion

7.1 Conclusions

This chapter starts with a summary of the conclusions from Chapters 2 to 6, thereby answering the research questions from Chapter 1. It gives an overview of the research challenges that are determined and the insights that are gained for different floricultural case studies and modelling approaches.

7.1.1 Research challenges

> ***RQ1:*** *What are research challenges in modelling logistics networks for perishable products induced by developments in the floricultural sector?*

To answer the first research question, a literature review has been conducted in three steps. First, a sector analysis provided the main SCM themes that require further investigation. Second, review articles that discuss the SCM themes were analysed to develop a conceptual research framework. Third, this framework was used to analyse relevant literature, which then resulted in a list of research challenges. The sector analysis consisted of desk research and three rounds of semi-structured interviews and workshops with sector experts in the Netherlands (i.e. people engaged in logistics at different stages in the floricultural supply chain). The review article analysis consisted of a collection of ten general SCM reviews, five food SCM reviews and two SCM reviews specifically addressing virtualising supply chains. The final literature analysis consisted of a collection of 71 articles that address a decision problem with context factors that can be found in the conceptual research framework and published from 2005 onwards.

The main SCM themes and subsequent SCM issues that were identified are (i) decision problems: network design and network control; (ii) context factors: supply and demand uncertainty, perishability, product and market differentiation; and (iii) objectives: efficiency, responsiveness and product quality. Most research is concerned with either network design (facility location in combination with flow, capacity, process or inventory allocation, transport mode or supplier selection) or network control (production planning, distribution planning, inventory management, transport management and evaluation of supply chains). Relating the context factors to the decision problems, the literature analysis showed that when dynamic or stochastic context factors are incorporated, the two decision problems (i.e. network design and network control) are more often integrated. Different objectives are addressed in different decision problems. Responsiveness as objective is found more in integrated network design and control, where product quality as objective is found only at the network control level. To solve the decisions problems, mostly optimisation techniques are used. When tactical or operational decisions are to be taken, i.e. network control or integrated network design and control problems, simulation is used. The combination of optimisation and simulation in a hybrid approach is not often found. This together has led to four research challenges (RCs).

Incorporation of product perishability at a network design level (RC1): Typically, next to biological variations, the quality of flowers and plants is determined by time and environmental conditions (such as temperature and humidity during transport). Customers demand guarantees on quality specifications, which leads to strict requirements on the logistics network concepts used in the sector and a need to incorporate product perishability in logistics decisions. In literature, incorporation of perishability is mainly embedded at the network control level, and extending it to the network design level is a notable research direction.

Addition of product quality to efficiency and responsiveness trade-off (RC2): One of the main logistics challenges for the sector is to deal with strong dynamics and uncertainty in supply and demand, regarding fresh product quality as well as the available volume in time at a specific place. The sector is characterised by last-minute changes and rush-orders. As a consequence, the required prediction and planning concepts and accompanying logistics system need to be very flexible and responsive. At the same time, costs and efficiency are still the main drivers for the sector, and being able to deliver good product quality is one of the success factors. A multi-objective approach to decision problems, in which a trade-off is made between efficiency, responsiveness and product quality, is an important research direction.

Integrated network design and control (RC3): The floricultural sector is subject to demand uncertainty, in product quantity as well as product quality, origin and timing. Furthermore, market differentiation is apparent in different logistics requirements from different sales channels (detail, e-tail and retail). Subsequently, there is a need for responsiveness in floricultural supply chains. The literature analysis has shown that these three aspects make integrating network design and control problems in the floricultural sector a promising research direction.

Hybrid optimisation and simulation (RC4): Optimisation is mostly used for network design, simulation is mostly used for network control. Just as the integration of decision problems is a research challenge, so is the integration of the applied modelling techniques.

In conclusion, the conceptual research framework and literature classification from Chapter 2, together with the described developments and industrial needs in the floricultural sector show that floricultural SCN research challenges can be found in integrated, quality-driven and responsive network design and control using hybrid optimisation and simulation.

7.1.2 Optimisation of the hub location problem

> ***RQ2:*** *What are optimal and robust logistics network designs for the European potted plant supply chain network?*

To answer the second research question, a case study in the European potted plant supply chain network was conducted. In cooperation with sector partners (auctions, trading organisations) and research institutes, characteristics of the potted plant sector were determined, relevant data was collected, and future developments were identified. A literature review on logistics orchestration was used to define three Logistics Orchestration Scenarios (LOSs). The LOSs were based on (combinations of) two possible chain performance improvement directions in network orchestration: enhanced logistics network design, i.e. use of a hub network to facilitate a better match of production and demand and a higher responsiveness; and logistics consolidation, i.e. in collection of products and in distribution to points of sale in order to better use truck capacity and to improve efficiency in routing. The first scenario then refered to the current situation where there is no hub network (LOS 0), the second scenario introduced a hub network (LOS 1) and the third scenario introduced consolidation in the hub network (LOS 2). A location-allocation problem was defined that represented the multi-level structure of the potted plant supply chain network. Then, a Mixed Integer Linear Programming (MILP) model was developed to solve the location-allocation problem and to evaluate the different LOSs for Europe. Different levels of orchestration in the LOSs lead to different transport costs, which was incorporated in the calculation of the transport cost parameters of the MILP.

Results show that a redesign of the network (LOS 1) can decrease costs by 19% and consolidation (LOS 2) can further decrease costs by 9%. The redesign mostly saves on transport time (28% decrease), while consolidation especially saves on kilometers and hence CO_2 emissions (9% decrease). The distribution from hubs to customer regions takes the biggest share in the costs (more than half), which makes consolidation in distribution more beneficial than consolidation in collection. For the redesign, the three hubs in the Netherlands as in the current situation (LOS 0), are supplemented with 12 hubs across Europe. The locations of the hubs are particularly directed by the most important countries for supply and demand (e.g. the Netherlands, Germany, and UK), but as a side effect also small countries in demand and supply volume (e.g. Russia) can be served responsively. Furthermore, the long distance flows form the foundation that is needed to constitute an efficient hub network. Without that volume the costs, working time and CO_2 emissions are close to the performance of the current network. The density of the hub network is determined by the short distance flows. To outperform the current situation, only 4 hubs are needed to improve on time, 5 hubs are needed to decrease costs and 11 hubs are needed to decrease CO_2 emissions. The increase in number of hubs furthermore shows a gradual and robust path of development, which is first aimed at covering the centre of Europe and then the east and south of Europe. Consolidation does not influence the location of hubs in the selected parameter settings.

With an eye on the future, if product volume grows by about 30%, costs increase with almost 60%, working time increases with around 70% and CO_2 emissions even increase with almost 90%. This is due to the fact that especially short distance flows are expected to grow, for which the hub network is less beneficial. Depending on the future trends concerning supply and demand volumes in South and East Europe, the importance of hubs in the south and east can grow compared to hubs in the centre of Europe. Collaboration between Dutch growers and within the retail market were furthermore identified to be most feasible. However, due to the short distance of Dutch growers to Dutch hubs and German growers taking the biggest share in total supply, and the rather high load factor of trucks to retail outlets, these collaborations would limit the benefits of consolidation.

In conclusion, gradually establishing hubs across Europe and consolidating flows as much as possible creates an opportunity for the European potted plant supply chain sector to improve costs, time and CO_2 emissions. The locations of the hubs are thereby guided by the long distance, large volume flows. The final density of the hub network is guided by the short distance flows.

7.1.3 Incorporating simulation and product quality decay

> ***RQ3:*** *What is the added value of increasing the complexity in modelling product quality and in the modelling approach used for a network design problem?*

To answer the third research question, three models, that differ in the way product quality is modelled, have been developed for the same network design problem. The first model was formulated as an MILP model which optimises an integrated hub location and process allocation problem (MILP-). The second model extended the first model by incorporating approximated product quality decay (MILP+). It was formulated as an MILP model that keeps track of product quality throughout the supply chain and sets constraints for the quality of the products delivered at the customers. The third model extended the second model by adding a simulation model that more accurately estimates product quality decay. It concerned a Hybrid Optimisation and Simulation (HOS) approach in which feedback from the simulation model is used to update the product quality constraints in the optimisation model. The three models were tested and compared for different problem instances with different network structures, different levels of uncertainty in the supply chain and different dynamics due to processing (e.g. for bundling, multiple products from different growers have to come together which effects the timing of the process as all products have to available for the process to start).

A comparison of MILP- and MILP+ in Chapter 4 shows that incorporating product quality in an MILP model increases product quality (vase life) by around 2%. A comparison of MILP+ and HOS in Chapter 4 shows that incorporating uncertainty in product quality (due to uncertainty in initial product quality and uncertainty in times and temperatures of logistics operations) in a HOS approach increases product quality by around 8%. Modelling product quality however increases costs by around 6% up to more than 10%. Increasing the complexity in product quality modelling thus benefits the quality of the products delivered at the customers, but depending on the case, it has to be seen whether it is worth the additional costs.

The literature review in Chapter 4 shows that there are different ways to combine optimisation and simulation models. When it is complex to include all decisions in one analytical model, a simulation model can be used as objective function in a heuristic, like local search. Furthermore, a simulation model can be developed in which (groups of) parameters are separately optimised. When the decision problem itself can be properly defined, but dynamics and stochastic factors cannot be incorporated accurately, using simulation as feedback for re-optimisation is suitable (Figueira & Almada-Lobo, 2014). The added value of feedback from a simulation is also shown by the HOS approach from Chapter 4. Only a HOS approach results in a network design that can deliver products with a quality that fulfills all customer requirements. The results furthermore show that when dynamics increase, the added value of the HOS approach increases. The MILP model does not include the dynamics due to processing (i.e. timing in processes) and therefore it benefits to add a simulation step with a higher degree of dynamics. When stochasticity increases, the results in Chapter 4 show that the added value of the HOS approach first increases, but then decreases again. Due to a higher level of uncertainty, the gap between delivered and required product quality in the simulation increases. This accelerates the update of the product quality constraints in the MILP, but overshoots the update when the gap becomes too large. Finally, results show that network structure affects the added value of a HOS approach. When the network structure mainly causes changes in the choice of locations rather than in the number of locations, the HOS approach is more suitable.

In conclusion, an increased level of complexity in modelling product quality decay is necessary to improve product quality within a network design problem. An increased level of complexity in the type of model used is essential to be able to fulfill product quality requirements.

7.1.4 Incorporating product quality decay and variability in product quality

> ***RQ4**: What are key factors in modelling product quality decay for a network configuration problem?*

To answer the fourth research question, an MILP model, that incorporates different aspects of product quality decay, has been developed for a network configuration problem. First, product quality was incorporated by classifying product flows within the network in quality categories and updating the classification throughout the supply chain based on the decay during transport, storage and processing. Then, variability in product quality was incorporated in the MILP model by differentiating the classification of product flows over more than one category. Last, different product quality parameters were incorporated in the MILP model, e.g. decay rates before and after processing, minimum quality requirements, price sensitivity to product quality. The model was run for different problem instances of the integrated hub location and process and stock allocation problem. The problem instances were used to test the computational efficiency of the model and to analyse the impact of different product quality settings for the model.

The results from Chapter 5 show that the structure of the network is particularly affected by the level of decay. Depending on the cost and revenue parameters, centralisation as well as decentralisation of the network can be a solution for coping with product quality decay. On the one hand, the network can be centralised to decrease handling time and hence the time that product quality is impaired (similar to Zhang et al. (2003)). On the other hand, more hubs can be opened to decrease transport times and hence decay (similar to Hwang (2004)). Changing decay rates due to processing mainly affect the level of postponement. When processing increases the decay rates, the level of postponement is high in order to process as late as possible. On the contrary, when processing decreases the decay rates, the level of postponement is low. When the level of postponement is low, stock can be moved to more central hubs to benefit from risk pooling. In case of variability in product quality, stocks and processes are also moved upstream to more central hubs. This may require that an additional hub is opened. Variability in product quality furthermore causes a split in product flows with high and low product quality.

In conclusion, the importance to incorporate product quality decay in network configuration increases with the level of decay and the level of variability in product quality.

7.1.5 Hybrid optimisation-simulation of logistics network problems for supply and demand driven perishable product supply chains

> ***RQ5**: What are suitable logistics networks for different supply and demand driven cut flower supply chains?*

To answer the fifth research question, a case study in the cut flower supply chain network was conducted. The case was based on the supply chain of a wholesaler who purchases cut flowers throughout the world and delivers the cut flowers to European florists. It was typified as a supply driven chain and the corresponding logistics network was typified as a centralised network with a logistics hub in the Netherlands. To identify the similarities and differences for supply and demand driven chains, scenarios were defined for supply driven (CODP at the customer location), intermediate supply-demand driven (CODP at a hub location) and demand driven (CODP at the grower location) chains. To identify the effect of product perishability, scenarios were defined with different levels of product quality decay. The optimal network was determined for each scenario using a hybrid optimisation-simulation approach. This modelling approach combined the models from Chapters 4 and 5. By using simulation in the modelling approach, the logistics network for each scenario was evaluated on several performance indicators related to efficiency, responsiveness and product quality. These performance evaluations were then used to rank the different logistics networks. As different actors in the network can have different objectives, the ranking was finally used to indicate the best logistics network from different perspectives.

Results show that the logistics networks for the supply and demand driven scenarios can differ in costs up to 15%. The average delivery times (i.e. time between order and delivery) can differ up to almost 200% when comparing the scenarios in which stock is held at the grower locations to the scenarios in which stock is held at a hub location. Average product quality (vase life) can differ up to 25%. In general, the optimal logistics networks are decentralised networks. However, to limit handling time and hence product quality decay, networks can be partly centralised. Since it is more expensive, in practice, to transport bouquets than to transport cut flowers, processes are allocated to hub locations close to customers. Central stock points would result in lower costs due to risk pooling, however, due to the lead time requirements of customers, central stock points would also result in storing bouquets which increases costs. Therefore, stocks are allocated to hub locations close to customers. Results furthermore show that costs do not necessarily increase when product quality decay is to be restricted. Next to decreasing transport costs, decentralisation of a logistics network decreases transport times, which in turn decreases product quality decay. Responsiveness of the logistics networks comes at the cost of product quality delivered to the customers and vice versa. To be able to deliver faster, more stocks are allocated. This increases the risk of products getting spoiled before they are ordered by customers, leading to more stock-outs. To be able to deliver products with the right quality, flows in the logistics network are reallocated. This benefits customers for which the requirements could not be met and harms customers for which the service levels were met beyond what was required.

In conclusion, the optimal logistics network configuration for perishable product supply chains is especially driven by the trade-off between responsiveness and product quality. As the sector is currently focused on efficiency, this would argue for a supply driven chain with the CODP at the customer location and a decentralised logistics hub network. When the focus shifts to responsiveness, the logistics hub network should be expanded with distribution hubs. When the focus would shift to delivering the right product quality, the CODP should be moved upstream the supply chain to the grower locations.

7.2 Integrated findings

In isolation, each chapter has its own research findings. Together, the chapters build up to findings that surpass the separate results. These integrated findings are now elaborated on along the dimensions of the research framework as given in Figure 1.2. This shows how the overall research objective is attained.

> ***Overall research objective:*** *To develop modelling approaches that support the (re)design of a perishable product logistics network for supply and demand driven supply chains.*

In Chapter 2, four research challenges are derived based on a literature review that draws on the characteristics of and developments within the floricultural sector. The research challenges are supported by additional literature reviews and focused to specific applications in Chapters 3 to 6. The research challenges furthermore relate to the different dimensions of this thesis' research framework, i.e. the system, consisting of the type of logistics network problem and the way product quality is addressed, and the modelling approach. The four research challenges are:

RC1: Incorporation of product perishability at a network design level. This relates to the system dimension and more specifically to the product quality dimension. Chapters 3 to 6 show an increasing complexity in modelling product quality, where Chapter 3 does not take product quality into account, Chapter 4 takes into account that product quality is dynamic and uncertain, Chapter 5 incorporates dynamic and variable product quality and Chapter 6 covers dynamic, variable and uncertain product quality.

RC2: Addition of product quality to efficiency and responsiveness trade-off. This relates to the performance within the system dimension as facilitated by the modelling approach dimension. Chapters 3 to 6 analyse the performance of logistics networks with respect to efficiency, defined as either costs or profits. Except for Chapter 4, the responsiveness of logistics networks is also analysed using delivery time and fulfillment (e.g. fill rate) as indicators. The performance of logistics networks with respect to minimum and average product quality is analysed in Chapters 4 to 6.

RC3: Integrated network design and control. This relates to the logistics network problem dimension given in the research framework. Chapters 3 to 6 show an increasing complexity in integrating strategic hub location with tactical process and stock allocation, where Chapter 3 studies a hub location problem, Chapter 4 integrates hub location with process allocation and Chapters 5 and 6 integrate hub location with process as well as stock allocation.

RC4: Hybrid optimisation and simulation. This relates to the modelling approach dimension in this thesis' research framework. In Chapters 3 and 5, optimisation is used to find a solution to the logistics network problem. In Chapters 3 and 5, a combination of optimisation and simulation is used.

Table 7.1 shows how the complexities in the research framework dimensions (Figure 1.2) are distributed over the different chapters. The distribution creates the opportunity to analyse the interaction between different dimensions. Table 7.2 shows the performance indicators that are used in the different chapters. This facilitates the comparison of networks along different dimensions.

Table 7.1: Complexity in research framework dimensions as covered in the thesis chapters

Research framework dimension			Chapter 3	Chapter 4	Chapter 5	Chapter 6
System	Logistics network problem	Hub location	✓	✓	✓	✓
		Process allocation		✓	✓	✓
		Stock allocation			✓	✓
	Product quality	Dynamic		✓	✓	✓
		Variability			✓	✓
		Uncertainty		✓		✓
Modelling approach		Optimisation	✓	✓	✓	✓
		Simulation		✓		✓

The next sections discuss the interaction between different research framework dimensions. First, the interaction within the system dimension is discussed, i.e. the effect of addressing product quality in different ways in different logistics network problems.

Table 7.2: Overview of indicators used to analyse the performance of networks in the thesis chapters

Performance category	Performance indicator	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Efficiency	Costs	✓	✓	✓	✓
	Profit			✓	✓
Responsiveness	Delivery time	✓		✓	✓
	Fulfillment				✓
Product quality	Minimum quality		✓	✓	✓
	Average quality			✓	✓

Then, the interaction between system and modelling approach dimensions is discussed. This is broken down into an analysis of the modelling approaches for individual system dimensions, i.e. a discussion on the type of logistics network problem in view of the modelling approach and a discussion on the way product quality is addressed in view of the modelling approach; and an analysis of the modelling approaches for the overall system dimension.

7.2.1 The interaction between logistics network problems and product quality

The literature analyses from Chapters 2, 4, 5 and 6 show that taking into account product quality decay in supply chain management problems is mostly dealt with on a tactical or operational level. The dynamic nature of product quality decay can be modelled more detailed and accurate on a small time scale. Strategic problems can include anticipated product quality decay at an aggregate level. Although taking into account estimated product quality improves the quality of the products delivered to the customers, it can still lead to insufficient product quality, e.g. the difference between delivered and required product quality can be as large as 6% (see Chapter 4), the difference between achieved and required percentages of sufficient quality products can be as large as 4% (see Chapter 6). Comparing the results from Chapters 3, 4, 5 and 6, the research in this thesis shows that *using an aggregate estimation of product quality does not guarantee adequate quality for the products delivered to customers.*

When perishability of products is not a factor, up to 28% can be saved in costs by using a hub network with consolidation of collection and distribution flows in the potted plants network (see Chapter 3). However, when the products are perishable, a hub network can lead to insufficient product quality in the order of 5% (see Chapter 4 and 6). If the negative effect on product quality is to be counteracted, a cost of up to 19% (see Chapter 4) has to be incurred. This would for a large part abolish the positive effect of flow consolidation on costs. On the other hand, if a higher product quality can be turned into higher revenues, the increase in costs can be compensated and profits can increase up to 2% (see Chapter 5). Taking into account product quality decay not only affects costs and profits, but also responsiveness of the network. Without product quality decay, using a hub network can decrease delivery time by as much as 38% (see Chapter 3). However, when decay is an issue and the logistics network design or configuration is adjusted for it, delivery time can increase up to 8% (see Chapter 6). When a minimum requirement is set for the quality of products delivered to customers, delivery speed and delivery reliability are improved (see Chapters 5 and 6). A minimum product quality requirement furthermore increases the reliability of the actual quality to match the required quality at the customer locations (see Chapter 6). *Incorporating product quality decay in logistics network design or configuration thus creates a more profitable and reliable network.*

The logistics network problems that are studied differ in network characteristics like demand volume, geography and scope. The results can therefore not be compared in absolute terms, but a comparison does reveal the key characteristics that have an impact on the logistics hub network. In general, the optimal design of a logistics hub network depends on the volumes and distances in the network (O'Kelly, 1992). The research in this thesis shows that the optimal design also depends on the product quality decay throughout the network. For a hub network, volume is needed to compensate the increase in fixed location costs by a decrease in variable transport costs. The volumes in Chapter 6 are much smaller than in Chapter 3 and hence the benefits of a hub network are much smaller. In addition, the distances in Chapter 6 are smaller than in Chapter 3. Distance is needed to benefit from the consolidation between hubs (O'Kelly, 1987). This is also shown in Chapter 3, where the costs decrease is much smaller if only local growers and customers use the hub network compared to the global grower and customer scope. Long distance flows determine the backbone of the network, i.e. the hub locations, and short distance flows follow. Similarly, flows of products that are price sensitive to quality determine the backbone of the network and flows of products for which a minimum product quality is required determine the configuration, i.e. flow, process and stock allocations 5. There are, however, differences in network configurations when it comes to different levels of decay (see Chapters 5 and 6) and different levels of uncertainty or variability in product quality (see Chapters 4, 5 and 6). In most cases, the difference can be found in the allocation of flows to limit quality decay. In other cases, the network is expanded when decay is more distortive. The expansion comprises the hub locations, but also the process and stock allocations. As can be seen in Chapters 4 and 6, more processes and stocks are allocated and flows are more scattered in logistics networks that are designed and configured while bearing in mind that the products are perishable.

It shows that the more logistics operations need to be executed within the supply chain, the more difficult it is to hedge product quality decay. The research in this thesis shows that *the design and configuration of a logistics network for perishable products not only depends on the distances and volumes in the network, but especially on the possibilities and difficulties to limit quality decay.*

7.2.2 The impact of the complexity in the logistics network problem on the modelling approach

Basic hub location problems, i.e. network design, can be well solved by optimisation models (Alumur & Kara, 2008). This is supported by the case study in Chapter 3. When also processes and stocks have to be allocated, i.e. network control, the problem becomes more complex (Melo et al., 2009). Processes, like bouquet-making and packaging, increase the size of products, which increases the costs of transport. Chapters 4, 5 and 6 show that hubs are located closer to customers to limit the final transport distances for the processed products. In addition, strict lead time requirements ask for nearby stock points, which moves the hub locations even more towards customers (see Chapters 5 and 6). In other words, allocation of processes and stocks create more dense networks. An increase in the density of the network implies an increase the number of hubs. This complicates the timing and planning in the network when multiple products from different origins need to be brought together at hubs to consolidate flows on the way to the customers or to be able to produce bouquets. The more complicated the timing in the network, the more difficult to capture these dynamics in a pure optimisation model (see Chapters 4 and 6). Research in this thesis shows that *integration of network design and network control problems increases dynamics in the network, which necessitates the use of a hybrid optimisation and simulation approach to solve the integrated problem.*

In general, the effectiveness of a hybrid optimisation and simulation approach depends on the problem characteristics (Figueira & Almada-Lobo, 2014). For the logistics network problems that are studied in this thesis, the addition of an iterative simulation step to the optimisation procedure does not change the locations within the hub network much, but particularly expands the hub network by adding hubs (see Chapter 6). However, the effectiveness of the hybrid approach can depend on the way the network changes with each iteration, e.g. the approach in Chapter 4 is most effective when the locations of hubs change with each iteration and less when the number of hubs changes. The results in this thesis show that *the development of a hybrid optimisation and simulation approach is much more subjected to the specific problem setting than the development of a pure optimisation model.*

7.2.3 The impact of the complexity in modelling product quality on the modelling approach

The modelling approaches are typified by optimisation and simulation models. Optimisation models are used to design or configure the optimal logistics network, simulation models are used to evaluate a logistics network. Due to the modelling flexibility of simulation (Van der Zee & Van der Vorst, 2005), the dynamic and stochastic nature of product quality can be more accurately modelled in simulation models than in optimisation models. Chapters 4 and 5 show how an aggregate approximation of product quality can be incorporated in an optimisation model and how (the accuracy of) the approximation improves the feasibility of the optimal network configuration. Still, product quality decay is often underestimated as is shown using simulation models in Chapters 4 and 6. The results point out that the logistics network configuration found by a pure optimisation model can be improved by a hybrid optimisation and simulation approach in which the difference between achieved and required product quality in the simulation model is used to steer the optimisation model. Research in this thesis shows that *a hybrid optimisation and simulation approach is needed to really capture product quality decay when designing and configuring a logistics network for perishable products.*

Optimisation and simulation models can be integrated in different ways. The literature review in Chapter 4 indicates that when the problem can be properly defined, but the dynamic and stochastic nature cannot be captured in an optimisation model, an iterative procedure is appropriate. This is supported in Chapters 4 and 6 for two different optimisation models. The optimisation model in Chapter 4 approximates the product quality decay on the complete path from grower to customer. The relatively high level of detail significantly increases run time for the optimisation model, but it also makes that product quality can be controlled rather precisely in the iterative hybrid approach. This precise control can limit the number of iterations needed to find a logistics network that can meet the product quality requirements. The level of detail in the optimisation model is key to the effectiveness of the hybrid approach with respect to run time and the feasible optimal logistics network that is eventually found. This is also shown in Chapter 6, where the detail in the optimisation model can be controlled by the number of product quality categories. Using it in an iterative procedure gives the opportunity to determine the right level of detail. It helps to prevent using a too high level of detail that unnecessarily eliminates low-cost opportunities or using a too low level of detail that favours infeasible opportunities. *A hybrid optimisation-simulation approach should control the level of detail with which product quality is incorporated in the optimisation model, as more detail increases run times significantly while it not necessarily contributes to finding the best logistics network configuration.*

7.2.4 The interaction between system characteristics and modelling approaches

The different chapters in this thesis discuss different products and markets with different characteristics. Detail and retail markets for potted plants are considered supply driven markets without predetermined requirements. Furthermore, the products are viewed as non-perishable. An optimisation model can be used for this relatively easy logistics network design problem. Due to the large volume handled in the European potted plant sector, a rather dense network is created and customers in the economic center can actually be served very responsively due to short delivery times (see Chapter 3). When products are more perishable, like cut flowers, it introduces supply uncertainty in product quality and quantity. This should be accounted for when designing the logistics network by introducing a simulation step in the optimisation approach (see Chapter 4 and 6). The logistics network is adjusted in order to limit the decay throughout the network which in turn improves the product quality that is in the end delivered to the customers. When markets are more demand-driven, like retail and e-tail markets for cut flowers, demand uncertainty increases and network control decisions become important (see Chapter 5 and 6). This adds to the need to introduce a simulation step in the optimisation approach. *Better capturing the dynamics and uncertainty in durations of logistics operations, product quality and product quantity, using a hybrid optimisation and simulation approach, assures that a logistics network is configured which is suitable for delivering products with the right quality in time.*

The different logistics networks throughout this thesis show the differences for the different products and markets. Although there is no overall design in this thesis for a logistics network that fits all different products and markets, the differences in the logistics networks resulting from different market requirements are limited when product quality decay is taken into account in the network design and control problem (see Chapter 6). The results show that *when product quality decay is taken into account in the optimisation of an integrated network design and control problem, selected hubs are complemented with new hubs when market requirements get more strict, while selected hubs are replaced by new hubs when product quality is not taken into account in the optimisation.*

7.3 Managerial implications

Within the DaVinc^{3}i project, discussions on the results of this thesis' research have stimulated the sense of urgency among the sector partners to assess the configuration of the logistics network. First of all, cost benefits of up to 28% have provided a clear stimulus for the design of a hub network. The configuration of the hub network should thereby be adapted to the type of supply chain.

For example (see Chapter 6):

- When flowers are distributed in a supply driven chain, a hub in the Netherlands can serve customers throughout Western Europe. When bouquets are distributed in a demand driven chain, multiple hubs close to the customers are needed to be able to deliver at the lowest costs.
- Due to virtualisation, florists could offer part of their large assortment virtually, ensuring that not all products have to be physically present at the stores. As a result, stocks and processes can be moved upstream in the supply chain towards growers.
- Demand driven supply chains have to cope with product quality guarantees. An increase in the number of hubs allows for more direct routes in the logistics network, which improves quality of the products delivered at the customer locations.

These kind of examples urged sector partners to think about whether their logistics network still fits their current supply chain. They reconsider the function of the existing locations, e.g. being a market place, a distribution hub with stock or a distribution hub without stock. Furthermore, they examine whether existing locations can be combined, closed or moved. This shows that the research supports the floricultural sector in the transition from a supply driven to a demand driven supply chain, while acknowledging the differences between products and markets and the trade-offs in efficiency, responsiveness and product quality.

Research in this thesis shows that long distance and large volume flows are a prerequisite for the (re)configuration of a hub network. Therefore, the logistics network should have a European scope. Due to the large number of small to medium-sized companies in the floricultural sector, it is expected that collaboration between multiple companies is necessary to bring enough volume together. Collaboration plays a prominent role in the floricultural sector, e.g. the auction originates from the collaboration between growers. However, to set up a hub network can be more difficult as it requires not only horizontal collaboration (i.e. collaboration between actors at the same level in the supply chain, like the cooperative of growers) but also vertical collaboration (i.e. collaboration between actors at different levels in the supply chain, like cooperation between a logistics service provider and a wholesaler). As shown in Chapter 3, especially collaboration between Dutch and non-Dutch companies in the scattered detail market is needed. An initiative linked to this, where a hub was opened in Bremen a couple of years ago, shows the difficulties of the collaboration. The location of the hub was foremost based on soft factors, as an opportunity to combine the local flows with global flows. This combination of flows can be favourable when the global flows are leading (see Chapter 3). When the logistics network is designed based on long distance flows while taking into account the perishability of the products, a collective, profitable and reliable network can emerge.

Research in this thesis shows the added value of using product quality information in logistics decisions. RFID tags on buckets and trolleys and scan moments throughout the floricultural supply chain provide information on the location of products, from which durations of logistics operations can be deduced. Combined with information on environmental conditions, quality of the products when delivered at the customer locations can be better predicted. Good quality estimates can improve the delivery reliability in the logistics network (see Chapter 6). Furthermore, product quality estimates could be used to set product prices. The auctions are based on such a price mechanism, where products are sorted in quality categories before they are auctioned per category. With improved product quality estimates throughout the supply chain, a variable price based on specific quality categories can be set for the final customers. This kind of price sensitivity can benefit the viability of a hub network (see Chapters 5 and 6).

7.4 Discussion and suggestions for further research

This section discusses the contributions, limitations and remaining research challenges in view of the research in this thesis. It starts with a discussion of topics related to the research framework (Figure 1.2) and identified research challenges (Chapter 2). Then, topics related to applicability and generalisability of the research are discussed.

7.4.1 Research framework and research challenges

The research in this thesis is discussed for each dimension in the research framework, i.e the system, including product quality decay and the logistics network problem, and the modelling approach. Each discussion is preceded by a short summary of the research contribution to the research challenges, i.e. (RC1) incorporation of product perishability at a network design level; (RC2) addition of product quality to efficiency and responsiveness trade-off; (RC3) integrated network design and control; (RC4) hybrid optimisation and simulation. The summary is followed by a general discussion in view of the dimension.

Product quality

In this thesis, models for network design problems are developed in which product quality is incorporated. The models are applied in case studies to gain insight in the trade-offs between costs, responsiveness and product quality. This contributes to the overall research objective and in particular to the first and second research challenge.

A review of the literature, published within the research period for this thesis (2011 to 2015), shows that within food and fresh produce SCM there is still limited attention to individual product characteristics (Shukla & Jharkharia, 2013a) and the relation of those product characteristics to logistics activities (Fredriksson & Liljestrand, 2014). The research in this thesis addresses one specific product characteristic, perishability, by modelling product quality decay for multiple products. Most research on perishability, does not take into account the gradual change of product quality over time. The contribution of the research in this thesis specifically lies in incorporating the dynamics of product quality decay. This leads to more accurate product quality approximations.

The research in this thesis contributes to the field of Quality Controlled Logistics (Van der Vorst et al., 2011). Fundamental for QCL is the use of quality decay models in logistics models. In this thesis, the degree-days model of Tromp et al. (2012) is used for this purpose. Tromp et al. (2012) show that the model has clear practical value, but also limitations. The model can predict remaining vase life of cut roses under specific conditions, but it can give prediction errors when the conditions differ. This prediction error then transfers to the models that are developed in this thesis. The error in these QCL models is expected to be moderate as the degree-days model is only used to get a rough estimation of product quality decay. Even so, future research could focus on determining the sensitivity of the QCL models to the quality decay model, e.g. using different quality decay estimations.

There is considerable experiment-based research for different cut flower cultivars to analyse changes in vase life under specific conditions, e.g. Safa et al. (2012); Kazemi (2012). However, general quality decay models, that can be used to determine quality decay under selectable conditions, are scarce. Future research could be focused on translating the experiment-based research to quality decay models to allow for a more flexible use of quality decay information in QCL. To limit the number of products that should be considered separately, developing general decay models might also help to categorise the vast amount of cut flower cultivars based on the way they react to environmental conditions. Furthermore, research in this thesis is mostly based on cut flowers due to the availability of information on product quality decay. Developing quality decay models for potted plants is more difficult as product quality can decay but also ameliorate. Future research could be focused on quality decay models for potted plants to be able to determine the impact of perishability in a potted plant logistics hub network.

Logistics network problem

In this thesis, models are developed for network design problems integrated with network control decisions. As part of the contribution to the overall research objective, this contributes to the third research challenge. However, the integration was limited to tactical decisions and the integration of operational decisions is left for further research.

The most integrated logistics network problem in this thesis is an integrated hub location and stock and process allocation problem. The combined integration of stock and process allocation enables a joined optimisation of network design and CODP allocation, which improves the network configuration. Although this integration of strategic and tactical decisions contributes to the research challenge to integrate problems at different decision levels, future research could extend the integration to operational decisions. For example, the integration of decisions on replenishment policies, production plans, vehicle routing, etc., in network design. Stock points are shown to be crucial for the performance of the network, which makes integration of operational stock decisions particularly interesting. This is also shown by the recent advancements in research on inventory-location models (e.g Wheatley et al., 2015).

Integration of operational decisions is even more important for perishable product supply chains, as perishability of products specifically emerges at the operational level. To exploit real-time information on product quality throughout the supply chain, future research could look into redirection of product flows based on actual product quality status or optimal adjustment of temperatures throughout the supply chain to achieve the required product quality at the end of the supply chain. This would contribute to the aim of QCL to create a logistics network that delivers the right product with the right quality to the right outlet on time at the lowest cost.

Modelling approaches

In this thesis, optimisation and simulation models are integrated in a hybrid optimisation and simulation approach. This contributes to the overall research objective and specifically to the fourth research challenge. However, one combination of models is analysed and analyses of other combinations or other modelling approaches is left for further research.

At the level of modelling approaches, this thesis shows a build-up to a hybrid optimisation and simulation approach. There are different ways to combine optimisation and simulation models. Based on the problem characteristics, i.e. the problem could be properly defined but dynamic and stochastic factors could not be incorporated accurately, it was decided to use a combination with a feedback loop. As the logistics network problem studied in this thesis is a more strategic and high-level problem, a pure optimal solution is often not needed and a heuristic search algorithm, using simulation to calculate the objective value, could be an alternative to find a near-optimal solution (e.g. Melouk et al., 2013). For future research, it would be worthwhile to investigate different ways to combine optimisation and simulation and to analyse which combination fits which setting. Research in this thesis confirms that hybrid approaches are quite dependent on the specific problem setting, so it would be useful to establish guidelines for the deployment of hybrid optimisation-simulation approaches.

There has been substantial progress in the development of stochastic optimisation models. The most used approach is stochastic programming, where the first stage is concerned with the location decisions and the second stage is concerned with the flow allocation decisions, e.g. Alumur et al. (2012); Contreras et al. (2011). In addition, fuzzy methods are used to deal with uncertainty in parameters and objective, e.g Khalili-Damghani et al. (2014). To prevent a worst-case network design, robust optimisation is receiving increased attention, e.g Hasani et al. (2014); Shahabi & Unnikrishnan (2014). Furthermore, chance-constrained programming is used to guarantee service levels with a given probability, e.g Mohammadi et al. (2013). Although there are several ways to deal with uncertainty in models, it still leaves the issue of capturing the dynamics of product quality decay. To include dynamic factors in an optimisation model, analytical queuing formulations have been used (Lieckens & Vandaele, 2012). The complexity of the model increases substantially when dynamic factors are included. Future research could then be aimed at developing optimisation models that can properly handle stochastic as well as dynamic factors and that are still solvable.

To solve the network design and configuration problems, a flow-based approach is used to formulate the MILP models in this thesis. Using a path-based approach like Baghalian et al. (2013) would facilitate the inclusion of dynamic and stochastic factors along the feasible paths through the network. However, it would also substantially increase the number of decision variables in the model, which could compromise run time. Baghalian et al. (2013) show results only for a small problem with three suppliers, three hubs and nine customers. When, in future research, solution methods can be improved with respect to the number of decision variables that can be handled, this can allow for the development of path-based models that can solve network design problems of real-world size.

7.4.2 Application and generalisation

Practical application in case studies

Due to the research being part of the DaVinc^{3}i project, a close cooperation with sector partners was readily established. This assisted in the formation of a clear picture of the floricultural sector. It showed the large share of small and medium-size enterprises and short term focus driven by day to day business, which at first conflicted with the long term focus of the DaVinc^{3}i project. It was a challenge to engage sector partners in an open discussion about the future of the floricultural sector and about the issues that need to be addressed to be prepared for that future. As a consequence, it was a challenge to find partners for case studies on strategic logistics network problems. Hence, a considerable part of the research in this thesis, although based on practical insights, is of a more theoretical nature.

The illustrative and real life cases that are used in this thesis are based on practice, but, inherent to modelling, assumptions about data and models are unavoidable. Discussions with sector experts on assumptions and preliminary results, sensitivity analyses and scenario approaches are used to justify the results. Future research could focus more on sensitivity analyses and multi-case studies to improve the validity of the results.

The gradually growing commitment to the DaVinc^{3}i project of the sector partners also showed the challenge to have supply chain actors with different interests to collaborate. The final case study in this thesis points out that the different objectives of supply chain actors result in different logistics networks. However, the first case study in this thesis points out that use of a hub network is only viable when there is enough volume, hence when supply chain actors collaborate. It is up to the industry to tackle this seeming contradiction and to show the willingness to collaborate, as has been done in the last century with the cooperative auction as shining example, to sustain the future of the floricultural sector.

Other supply chain networks

Up till now, the discussion is focused on floriculture. In Chapter 2 it is shown, however, how FlSCM is closely related to food SCM and perishable product SCM. The characteristics of the floricultural supply chains are similar to food supply chains and more generally to agricultural product supply chains. This especially holds for the high supply uncertainty due to seasonality, differing growing conditions for different growing areas, etc. High demand uncertainty is a phenomenon that is inevitably present in almost every supply chain nowadays. The use of hybrid optimisation and simulation approaches in this thesis shows how supply and demand uncertainty and perishability of products can be dealt with. The developed models can therefore also be applied to perishable product supply chains other than floriculture.

A key difference between food supply chains and floricultural supply chains is that food supply chains are more demand driven and that retail and e-tail take a bigger market share. Therefore, applicability of the results for food supply chains is mainly related to the results for the demand driven networks. Applicability of the results for floricultural supply chains is mainly related to the transition from a supply to a demand driven chain and the differences between the logistics networks.

An example of the applicability of this thesis' research, to processed food supply chains, are the results from Chapter 5 with decreasing decay rates. Processing of food, e.g. refrigeration, can slow down decay, which would mean that processes should be executed as soon as possible (Blackburn & Scudder, 2009). The large variety in end-products for which similar input products are used would argue for storing raw material and postponing the processes until it is known what end-product to use the stored products for (Kilic et al., 2013). These trade-offs in postponement and CODPs are often analysed in isolation, but this thesis shows that the location of the hubs plays a significant role in the allocation of optimal CODPs. In general, although the results are case specific, the mechanisms that underlie the results in this thesis can be useful for other supply chains than floricultural supply chains. It shows the relevance of the research not only for FlSCM but also for food and perishable product SCM.

Food decay is often modelled by exponential functions. Decay of nuclear products can also be modelled by exponential functions (Nagurney & Nagurney, 2012). This creates opportunities to apply the models developed in this thesis for the (re)design of nuclear and energy supply chain networks. Opportunities might furthermore be found in supply chain networks for perishable products like medicine or chemicals. Using information on product quality in logistics decisions might especially be valuable in biorefinery supply chain networks. With the competing markets (Singh et al., 2014), product quality estimates could be used to determine real-time which products to sent to the food market and which products to use for biorefining.

Next to studies of individual sectors, further research could be focused on a collection of sectors that can supplement each other. There are differences in the key characteristics of sectors, in the way the supply chain is organised, the developments that have to be dealt with, etc. The different characteristics could provide joint capabilities that cannot be achieved individually. For example, gyps is transported from Israel to the Netherlands and carrots are transported in the opposite direction. Combining these kind of complementary flows could increase the viability of a logistics hub network.

Final remarks on societal relevant topics

Product quality decay can lead to waste. Especially food waste is a concern in modern society (Shukla & Jharkharia, 2013a). In Chapter 4, it is shortly discussed how different network designs effect the level of waste. However, the focus in this thesis was more on the dynamics rather than the consequences of product quality decay. In addition, sustainability is an increasing concern in modern society and it receives increasing attention in research on network design (e.g. Mohammadi et al., 2014). In Chapter 3, the consequences of network redesign for CO_2 emissions are discussed. Although the focus in this thesis was on product quality decay, the designs in Chapter 3 compared to the designs in Chapters 4, 5 and 6, suggest that sustainable and perishable product network designs do not have to differ much. Limiting transport times and transport distances in the logistics network can help to cope with either sustainability or product quality decay in network design.

Growing concerns about sustainability in logistics increases the demand for locally produced and locally distributed products to decrease the emissions from transport. At a national or regional scale, transport times are short and in that short time, the environmental conditions during logistics operations have less impact on product quality. It could then suffice to incorporate time restrictions in network design problems, e.g. Etemadnia et al. (2015) develop a model in which hub locations close to production and customer regions are more likely to be selected and Firoozi et al. (2013) adjust stock parameters to account for a maximum storage time of products. Although the models developed in this thesis can also deal with time restrictions by replacing product quality decay parameters by duration parameters, they could be unnecessarily complex for these settings. The focus in this thesis was on the global floricultural sector rather than on local networks and the long distances make product quality decay an important aspect to take into account in the floricultural network design problems.

The research in this thesis contributes to the fields of Operations Management, Operations Research and Quality Controlled Logistics. As every question answered raises new questions, the thesis is intended to present the research contributions as well as to inspire fellow researchers.

Summary
Samenvatting
Publications
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About the author
Completed training and supervision plan

Summary

Floriculture is inseparably linked to the Netherlands. The profound knowledge of the Dutch on how to breed and grow cut flowers and potted plants, the Dutch flower auctions being the largest in the world, the adequate infrastructure to facilitate transport and logistics; it has made the Dutch floricultural sector to what it is today: the trading hub for Europe.

The floricultural sector is, however, confronted with new developments that will change the network. To be able to respond to and be prepared for the consequences of the developments, a consortium of industry professionals and academics started the project DaVinc^{3}i (Dutch Agricultural Virtualized International Network with Coordination, Consolidation, Collaboration and Information availability) in 2011. Over 4 years, DaVinc^{3}i has evolved into a community of sector partners, which facilitated the research for this thesis.

The floricultural sector needs to handle different products with different levels of perishability (i.e. product quality decay), coming from different grower regions and going to different international customer regions, in order to meet differentiated market requirements. The developments cause a shift in grower and customer regions, which asks for redesign of the logistics network towards a European hub network. Furthermore, the developments cause a shift in market shares from detail markets (i.e. specialised sales channel like florists) to retail markets (i.e. unspecialised sales channel like supermarkets) and e-tail markets (i.e. web-shops), which causes the floricultural supply chain network to shift from being supply driven to becoming more demand driven. Corresponding hub networks should be designed and evaluated to gain insight in the performance, sensitivities and robustness of logistics networks for future scenarios. The related decisions regarding the logistics networks and the complexity in (the combination of) decisions calls for quantitative models that can assist in the decision-making. Different types of models are thereby suitable for different types of logistics network problems and problem characteristics.

> ***Overall research objective:*** *To develop quantitative modelling approaches that support the (re)design of a perishable product logistics network for supply and demand driven supply chains.*

Derived from the overall research objective, five research questions have been formulated. To answer the first research question, *"What are research challenges in modelling logistics networks for perishable products induced by developments in the floricultural sector?"*, a sector analysis and literature review were conducted. The sector analysis resulted in three main Supply Chain Management (SCM) themes and subsequent SCM issues that required further investigation. The first theme is related to decision problems, which comprises network design and network control. The second theme is related to context factors, which comprises supply and demand uncertainty, perishability, product and market differentiation. The third theme is related to objectives, which comprises efficiency, responsiveness and product quality. These SCM themes, together with an analysis of SCM literature, resulted in a conceptual research framework and consequently in an identification of research gaps and challenges. Results showed that Floricultural SCM research challenges can be found in:

- *Incorporation of product perishability at a network design level*
  Customer guarantees on product quality lead to a need to incorporate product perishability in logistics decisions. Up to now, perishability is mainly incorporated at the operational network control level and extending it to the strategic network design level is a notable research direction.
- *Addition of product quality to efficiency and responsiveness trade-off*
  Costs and, more generally, efficiency are the main drivers for the sector, last-minute changes and rush-orders require flexibility and responsiveness and being able to deliver good product quality is one of the success factors. A multi-objective approach to decision problems, in which a trade-off is made between efficiency, responsiveness and product quality, is an important research direction.
- *Integrated network design and control*
  The floricultural sector is subject to demand uncertainty, needs responsive logistics and allows for market differentiation. These three aspects make integrating network design and control problems a promising research direction.
- *Hybrid optimisation and simulation*
  Optimisation is mostly used for network design, simulation is mostly used for network control. Just as the integration of decision problems is a research challenge, so is the integration of the applied modelling techniques.

The first three research challenges relate to the type of logistics network problem and the way product quality is addressed. This is denoted as the *system*. The fourth research challenge relates to the *modelling approach*. The system and modelling approach dimensions are the foundation for the research framework of this thesis. The research framework is developed to structure and expose the complexities within the system and modelling approach dimensions, which is then used to define the remaining research questions in this thesis.

To answer the second research question, *"What are optimal and robust logistics network designs for the European potted plant supply chain network?"*, a case study in the European potted plant supply chain network was conducted. In cooperation with sector partners (auctions, trading organisations) and research institutes, characteristics of the potted plant sector were determined, relevant data was collected, and future developments were identified. In response to the developments, three Logistics Orchestration Scenarios (LOSs) were defined based on (combinations of) two possible chain performance improvement directions in network orchestration: logistics network design and logistics consolidation. A location-allocation problem was defined and a Mixed Integer Linear Programming (MILP) model was developed to solve the location-allocation problem and to evaluate the different LOSs for Europe.

Results show that gradually establishing hubs across Europe and consolidating flows as much as possible creates an opportunity for the European potted plant supply chain sector to improve costs, time and CO_2 emissions. For the redesign, the three existing hubs in the Netherlands are supplemented with 12 hubs across Europe. The locations of the hubs are thereby guided by the long distance and large volume flows. The number of hubs is guided by the short distance flows. Depending on the future trends concerning supply and demand volumes in South and East Europe, the importance of hubs in the south and east can grow compared to hubs in the centre of Europe.

To answer the third research question, *"What is the added value of increasing the complexity in modelling product quality and in the modelling approach used for a network design problem?"*, three modelling approaches have been developed that differ in the way product quality is modelled. The first model was formulated as an MILP model which optimises an integrated hub location and process allocation problem (MILP-). The second model extended the first model by incorporating approximated product quality decay and setting constraints for the quality of the products delivered at the customers (MILP+). The third model, a Hybrid Optimisation and Simulation (HOS) approach, extended the second model by using feedback from a simulation model to update the product quality constraints in the optimisation model.

It is shown that the convergence of the HOS approach depends on the gap between the product quality requirements and the quality that can be delivered according to the simulation. The added value of the HOS approach depends on whether the network structure mainly causes changes in the choice of locations rather than in the number of locations. A comparison of MILP-, MILP+ and HOS shows that an increased level of complexity in modelling product quality decay is necessary to improve product quality within a network design problem and an increased level of complexity in the type of model used is essential to be able to fulfill product quality requirements.

To answer the fourth research question, *"What are key factors in modelling product quality decay for a network configuration problem?"*, an MILP model has been developed for the integrated hub location and process and stock allocation problem that incorporates different aspects of product quality decay. Product flows within the network were classified in quality categories and the classification was updated throughout the supply chain based on the decay during transport, storage and processing. In addition, the classification of product flows was differentiated over more than one category to include variability in product quality. The MILP model included different product quality parameters, e.g. decay rates before and after processing, minimum quality requirements, price sensitivity to product quality.

Results show that the structure of the network is particularly affected by the level of decay, where centralisation as well as decentralisation of the network can be a solution for coping with product quality decay. Changing decay rates due to processing mainly affect the level of postponement (i.e. postponing processes that make products more customer specific (Forza et al., 2008)). An increase in decay rates increases the level of postponement in order to process as late as possible, a decrease in decay rates decreases the level of postponement which allows stocks to be moved to more central hubs. In case of variability in product quality, stocks and processes are also moved upstream to more central hubs, which may require that an additional hub is opened. Variability in product quality furthermore causes a split in product flows with high and low product quality. Overall, the importance to incorporate product quality decay in network configuration increases with the level of decay and the level of variability in product quality.

To answer the fifth research question, *"What are suitable logistics networks for different supply and demand driven cut flower supply chains?"*, a case study in the cut flower supply chain network was conducted. The case was based on the supply driven chain of a wholesaler that purchases cut flowers throughout the world and delivers the cut flowers to European florists. Scenarios were defined for supply driven, intermediate supply-demand driven and demand driven chains and for different levels of product quality decay. For each scenario, the optimal network was determined using a hybrid optimisation-simulation approach. The optimal networks were evaluated on performance indicators related to efficiency, responsiveness and product quality. These performance evaluations were then used to rank the different logistics networks.

Results show that the logistics networks for supply and demand driven scenarios significantly differ in costs, lead times and product quality (vase life). The optimal logistics network configuration for cut flower supply chains is especially driven by the trade-off between responsiveness and product quality. As the floricultural sector is currently focused on efficiency, this would argue for a supply driven chain with a decentralised network in which processes and stocks are allocated to the customer locations. When the focus shifts to responsiveness, the logistics hub network should be expanded with hubs close to the customers. When the focus would shift to delivering the right product quality, processes and stocks should be moved upstream the supply chain to the grower locations.

Integrated findings

Concerning the interaction between the logistics network problem and product quality decay, the gained insights are:

- Using an aggregate estimation of product quality in a logistics network problem does not guarantee adequate quality for the products delivered to customers. Different product quality factors need to be incorporated, like the level of product quality decay and variability in product quality. Furthermore, a minimum requirement should be set for the quality of products delivered to customers. This not only improves the reliability of the actual quality to match the required quality at the customer locations, but also the delivery speed and delivery reliability.
- Incorporating product quality decay in logistics network design or configuration creates a more reliable and profitable network. However, when more logistics operations need to be executed within the supply chain, it is more difficult to hedge product quality decay.
- Where the design and configuration of a logistics network for general products depends on the distances and volumes in the network, the design and configuration of a logistics network for perishable products especially depends on the possibilities and difficulties to limit quality decay.

Concerning the interaction between the system, i.e. the type of logistics network problem and the way product quality decay is addressed, and modelling approach, the gained insights are:

- Integration of network design and network control problems increases dynamics in the network. This necessitates the use of a hybrid optimisation and simulation approach to solve the integrated problem.
- A hybrid optimisation and simulation approach is needed to really capture product quality decay when designing and configuring a logistics network for perishable products.
- A hybrid optimisation and simulation approach should control the level of detail with which product quality is incorporated in the optimisation model, as more detail increases run times significantly while it not necessarily contributes to finding the best logistics network configuration.
- A hybrid optimisation and simulation approach is much more subjected to the specific problem setting than the development of a pure optimisation model.

In conclusion, better capturing the dynamics and uncertainty in durations of logistics operations, product quality and product quantity, using a hybrid optimisation and simulation approach, assures that a logistics network is configured which is suitable for delivering products with the right quality in time.

Managerial implications

Within the DaVinc^{3}i project, discussions on the results of this thesis' research have stimulated the sense of urgency among the sector partners to assess the configuration of the logistics network. First of all, cost benefits of up to 28% have provided a clear stimulus for the design of a hub network. The configuration of the hub network should thereby be adapted to the type of supply chain. Several examples urged sector partners to think about whether their logistics network still fits their current supply chain. They reconsider the function of the existing locations and examine whether existing locations can be combined, closed or moved. This shows that the research supports the floricultural sector in the transition from a supply driven to a demand driven supply chain, while acknowledging the differences between products and markets and the trade-offs in efficiency, responsiveness and product quality.

Research in this thesis shows that a logistics hub network should be designed with a European scope. Due to the large number of small to medium-sized companies in the floricultural sector, it is expected that collaboration between multiple companies is necessary to bring together the volume that is needed to justify the use of a hub network. When the logistics network is designed based on long distance flows while taking into account the perishability of the products, a collective, profitable and reliable network can emerge. When product quality estimates can be used to set product prices for the final customer, this benefits the viability of a hub network.

Discussion and further research

A research discussion gives rise to suggestions for further research, summarized as:

- Within food and fresh produce SCM there is still limited attention to individual product characteristics and the relation of those product characteristics to logistics activities. The research in this thesis addresses one specific product characteristic, perishability, by modelling product quality decay for multiple products.
- In this thesis' research, logistics and quality decay models are combined. Future research could focus on determining the sensitivity of the developed models to the quality decay model used.
- The combined integration of stock and process allocation enables a joined optimisation of network design and customer order decoupling point allocation, which improves the network configuration. Future research could extend the integration of strategic and tactical decisions to also integrate operational decisions, especially as perishability of products specifically emerges at the operational level.

- This thesis shows a build-up to a hybrid optimisation and simulation approach. There are different ways to combine optimisation and simulation models. For future research, it would be worthwhile to investigate different ways to combine optimisation and simulation and to analyse which combination fits which setting.
- There has been substantial progress in the development of stochastic optimisation models and optimisation models that include dynamic factors. Future research could be aimed at developing optimisation models that can properly handle stochastic as well as dynamic factors and that can still solve problems of real-world size.
- It is shown that the insights gained in this thesis can be used to support supply chain networks other than the floricultural supply chain network, e.g. food, energy, medicine, chemical and biorefinery. Further research could then be focused on a collection of sectors that can supplement each other to increase the viability of a logistics hub network.

Samenvatting

Sierteelt is onlosmakelijk verbonden met Nederland. De grondige kennis die in Nederland aanwezig is omtrent groei en bloei van bloemen en planten, de grootste bloemenveiling van de wereld die in Nederland staat, de adequate infrastructuur voor transport en logistiek; het heeft ervoor gezorgd dat de Nederlandse sierteeltsector de spil is geworden in de Europese bloemen- en plantenmarkt.

De sierteeltsector wordt echter geconfronteerd met nieuwe ontwikkelingen die de markt en het bijbehorende distributienetwerk (gaan) veranderen. Om te kunnen reageren en voorbereid te zijn op de consequenties van die ontwikkelingen is een consortium van sectordeskundigen en academici het DaVinc^{3}i (Dutch Agricultural Virtualized International Network with Coordination, Consolidation, Collaboration and Information availability) project gestart in 2011. In de daaropvolgende vier jaar is DaVinc^{3}i uitgegroeid tot een community voor sectorgenoten, daarbij ondersteuning gevend aan het onderzoek voor dit proefschrift.

De sierteeltsector moet omgaan met verschillende producten die onderhevig zijn aan een verschillende mate van bederfelijkheid, die van verschillende kwekerregio's afkomstig zijn en die naar verschillende internationale klantregio's moeten worden gedistribueerd, om daarbij te voldoen aan verschillende markteisen. De ontwikkelingen zorgen ervoor dat kweker- en klantregio's verplaatsen. Dit heeft tot gevolg dat het huidige logistieke netwerk moet worden uitgebreid tot een Europees hub netwerk. De ontwikkelingen zorgen er daarnaast voor dat het marktaandeel van de detail markt (i.e. specialistisch afzetkanaal, zoals bloemisten) afneemt en dat het marktaandeel van de retail (i.e. afzetkanaal niet gespecialiseerd in sierteelt, zoals supermarkten) en e-tail markt (i.e. web shops) toeneemt. Dit betekent dat het type keten verandert van aanbod-gestuurd naar meer vraag-gestuurd. De hubnetwerken voor de verschillende typen ketens moeten worden ontworpen en geëvalueerd om inzicht te krijgen in prestaties, gevoeligheden en robuustheid van logistieke netwerken voor toekomstscenario's. De bijbehorende logistieke beslissingen, en de complexiteit in (de combinatie van) beslissingen, vereisen een kwantitatieve aanpak die het beslisproces ondersteunt.

Algemeen onderzoeksdoel: *Het ontwikkelen van kwantitatieve modellen ter ondersteuning van het (her)ontwerp van een logistiek netwerk voor bederfelijke producten in aanbod-gedreven en vraag-gestuurde ketens.*

Van het algemene onderzoeksdoel zijn vijf onderzoeksvragen afgeleid. De eerste onderzoeksvraag, *"Wat zijn de uitdagingen bij het modelleren van logistieke netwerken voor bederfelijke producten in relatie tot de ontwikkelingen in de sierteeltsector?"*, is beantwoord aan de hand van een sectoranalyse en literatuurstudie. De sectoranalyse resulteerde in drie Supply Chain Management (SCM) thema's en daaruit volgende SCM vraagstukken die verder onderzoek behoeven. Het eerste thema is gerelateerd aan beslisproblemen, bestaande uit netwerkontwerp en netwerkbesturing. Het tweede thema is gerelateerd aan context factoren, bestaande uit aanbod- en vraagonzekerheid, bederfelijkheid, product- en marktdifferentiatie. Het derde thema is gerelateerd aan doelstellingen, bestaande uit efficiëntie, responsiviteit en productkwaliteit. Deze SCM thema's, gecombineerd met een analyse van SCM literatuur, hebben geleid tot een conceptueel onderzoeksraamwerk en een uiteenzetting van hiaten en uitdagingen in SCM onderzoek met betrekking tot de sierteeltsector. De onderzoeksuitdagingen zijn:

- *Rekening houden met afnemende productkwaliteit bij netwerkontwerp-beslissingen*
  Klanteisen met betrekking tot productkwaliteit zorgen ervoor dat rekening moet worden gehouden met bederfelijkheid bij het nemen van logistieke beslissingen. Dit wordt voornamelijk gedaan op een operationeel niveau in beslissingen rondom netwerkbesturing. De uitdaging is om dit uit te breiden naar strategische netwerkontwerp-beslissingen.
- *Toevoegen van productkwaliteit aan de efficiëntie-responsiviteit afweging*
  Kosten en, meer algemeen, efficiëntie zijn de voornaamste drijfveer voor de sector. Last-minute aanpassingen en spoedorders vragen om flexibiliteit en responsiviteit. Het succes van de sector zit in het kunnen leveren van producten met hoge kwaliteit. Een multi-objective benadering van beslisproblemen, waarin een afweging wordt gemaakt tussen efficiëntie, responsiviteit en productkwaliteit, is een belangrijke onderzoeksrichting.
- *Integratie van netwerkontwerp en -besturing*
  De sierteeltketen kampt met vraagonzekerheid, vraagt om een responsief logistiek netwerk en geeft mogelijkheid tot marktdifferentiatie. Deze drie aspecten maken de integratie van vraagstukken omtrent netwerkontwerp en netwerkbesturing een veelbelovende onderzoeksrichting.
- *Hybride optimalisatie en simulatie*
  Optimalisatie wordt vooral toegepast bij netwerkontwerp-problemen, simulatie wordt vooral toegepast bij besturingsproblemen. Net als de integratie van beslisproblemen is het een uitdaging om modelleringstechnieken te integreren.

De eerste drie onderzoeksuitdagingen zijn gerelateerd aan het type probleem en de manier waarop productkwaliteit daarin wordt meegenomen. Dit wordt aangeduid met het *systeem*. De vierde onderzoeksuitdaging is gerelateerd aan *model* typen. De systeem dimensie en model dimensie vormen de basis voor het onderzoeksraamwerk van dit proefschrift. Het raamwerk is ontwikkeld om de complexiteit in de dimensies bloot te leggen en te structureren. Dit is vervolgens gebruikt om de overige onderzoeksvragen in dit proefschrift te definiëren.

Om de tweede onderzoeksvraag, *"Wat is een optimaal en robuust logistiek netwerkontwerp voor de Europese potplanten keten?"*, te beantwoorden is een case studie uitgevoerd in het netwerk van Europese potplanten ketens. In samenwerking met sectordeskundigen (veiling, handelsorganisaties) en onderzoeksinstellingen zijn karakteristieken van de potplantensector achterhaald, is relevante data verzameld en zijn toekomstige ontwikkelingen geïdentificeerd. In antwoord op de ontwikkelingen zijn drie Logistieke Orchestratie Scenario's (LOSs) gedefinieerd die daarbij gebaseerd zijn op (combinaties van) twee mogelijke ketenverbeteringen: logistiek netwerkontwerp en logistieke consolidatie. Er is een locatie-allocatie probleem gedefinieerd en een Mixed Integer Linear Programming (MILP) model ontwikkeld om het locatie-allocatie probleem op te lossen en om de verschillende LOSs voor Europa te evalueren.

De resultaten laten zien dat het geleidelijk opzetten van hubs door heel Europa en het zo veel mogelijk consolideren van productstromen, een kans is voor de Europese potplantensector om kosten, tijd en CO_2 emissies te besparen. Voor het ontwerp moeten de bestaande hubs in Nederland worden aangevuld met 12 hubs door Europa heen. De locaties van de hubs worden daarbij bepaald door de productstromen met een lange afstand tussen herkomst en bestemming en met een groot volume. De productstromen met een korte afstand tussen herkomst en bestemming bepalen het aantal hubs. Afhankelijk van de toekomstige vraag en aanbod trends in Zuid en Oost-Europa, kan het belang van de hubs in het zuiden en oosten toenemen ten opzichte van de hubs in Centraal-Europa.

Om de derde onderzoeksvraag, *"Wat is de toegevoegde waarde van een toenemende complexiteit in het modelleren van productkwaliteit en in het type model voor een netwerkontwerp-probleem?"*, te beantwoorden zijn drie benaderingen voor model ontwikkeling gekozen waarin productkwaliteit op verschillende manieren is gemodelleerd. Het eerste model is geformuleerd als een MILP model voor het optimaliseren van een geïntegreerd hublocatie en proces-allocatie probleem (MILP-). Het tweede model is een uitbreiding op het eerste model en omvat een schatting van het productkwaliteitsverloop in het netwerk die wordt gebruikt om beperkingen toe te voegen die een minimale kwaliteit garanderen van de producten die aan klanten geleverd worden (MILP+). Het derde model, een Hybride Optimalisatie en Simulatie (HOS) aanpak, is een uitbreiding op het tweede model en gebruikt de output van het simulatiemodel om de kwaliteitsbeperkingen in het optimalisatiemodel te verbeteren.

Het is aangetoond dat de convergentie van de HOS aanpak afhangt van het verschil tussen de kwaliteit die geleverd wordt aan klanten in de simulatie en de gestelde kwaliteitseisen. De toegevoegde waarde van de HOS aanpak hangt af van de veranderingen in het netwerkontwerp, of die vooral gevonden worden in de locatiekeuze of in het aantal locaties. Een vergelijking van MILP-, MILP+ en HOS laat zien dat, om de geleverde productkwaliteit in een netwerkontwerp-probleem te verbeteren, een toenemende complexiteit in het modelleren van productkwaliteitsverloop nodig is. Een toenemende complexiteit in het type model dat wordt gebruikt is essentieel om aan de kwaliteitseisen te kunnen voldoen.

Om de vierde onderzoeksvraag, *"Wat zijn belangrijke factoren in het modelleren van productkwaliteitsverloop voor een netwerkconfiguratie-probleem?"*, te beantwoorden is een MILP model ontwikkeld voor het geïntegreerde hublocatie en proces en voorraad-allocatie probleem met daarin verschillende aspecten van productkwaliteitsverloop. Productstromen in het netwerk zijn geclassificeerd aan de hand van kwaliteitscategorieën en de classificatie wordt door de keten heen bijgewerkt als gevolg van het kwaliteitsverlies tijdens transport, opslag en verwerking. De classificatie wordt bovendien gespreid over meerdere categorieën om zo de variabiliteit in productkwaliteit mee te nemen. Het MILP model bevat verschillende parameters gerelateerd aan productkwaliteit, bijvoorbeeld de mate van kwaliteitsverval voor en na verwerking, een minimum kwaliteitseis en prijsgevoeligheid voor productkwaliteit.

De resultaten laten zien dat de structuur van het netwerk vooral wordt beïnvloed door de mate van kwaliteitsverval, waarbij zowel centralisatie als decentralisatie van het netwerk een oplossing kunnen zijn voor het omgaan met productkwaliteitsverloop. Wanneer een proces de mate van kwaliteitsverval verandert, dan heeft dit vooral effect op de allocatie van die processen. Een toename in de mate van kwaliteitsverval zorgt ervoor dat processen zo laat mogelijk in de keten worden uitgevoerd, een afname in de mate van kwaliteitsverval zorgt ervoor dat processen zo vroeg mogelijk worden uitgevoerd wat tegelijkertijd de mogelijkheid geeft om voorraden te verplaatsen naar centraal gelegen hubs. Wanneer er sprake is van variabiliteit in productkwaliteit, dan worden voorraden en processen verplaatst naar meer centraal gelegen hubs, wat kan leiden tot een toename in het aantal hubs. Variabiliteit in productkwaliteit zorgt er verder voor dat er een duidelijke splitsing ontstaat in productstromen met een hoge en lage productkwaliteit. In het algemeen neemt het belang van het meenemen van productkwaliteitsverloop in een netwerkconfiguratie-probleem toe met de mate van kwaliteitsverval en de mate van variabiliteit in productkwaliteit.

Om de vijfde onderzoeksvraag, *"Wat zijn geschikte logistieke netwerken voor verschillende aanbod-gedreven en vraag-gestuurde snijbloemen ketens?"*, te beantwoorden is een case studie uitgevoerd in het netwerk van snijbloemen ketens. De case is gebaseerd op een aanbod-gestuurde keten rondom een groothandelaar die snijbloemen van over de hele wereld inkoopt en distribueert naar Europese bloemisten. Er zijn scenario's gedefinieerd voor aanbod-gedreven tot vraag-gestuurde ketens met verschillende mate van kwaliteitsverval. Voor elk scenario is het optimale logistieke netwerk bepaald met behulp van een hybride optimalisatie-simulatie aanpak. De optimale netwerken zijn geëvalueerd aan de hand van prestatie-indicatoren gerelateerd aan efficiëntie, responsiviteit en productkwaliteit. Deze evaluatie is vervolgens gebruikt om een ranking te maken van de verschillende logistieke netwerken.

De resultaten laten zien dat de logistieke netwerken voor aanbod-gestuurde en vraag-gedreven ketenscenario's significant verschillen in kosten, doorlooptijden en productkwaliteit. De optimale logistieke netwerkconfiguratie voor snijbloemen ketens wordt vooral gestuurd door de afweging tussen responsiviteit en productkwaliteit. De focus op efficiëntie in de sierteeltsector pleit voor een aanbod-gestuurde keten met een gedecentraliseerd netwerk waarin processen en voorraden bij de klant zijn gealloceerd. Als de focus verschuift naar responsiviteit, dan zou het logistieke hub netwerk moeten worden uitgebreid met dicht bij de klant gelegen hubs. Als de focus verschuift naar het leveren van de juiste productkwaliteit, dan zouden de processen en voorraden richting de kwekers moeten schuiven.

Belangrijkste bevindingen

De volgende inzichten zijn verkregen betreffende de interactie tussen het logistieke netwerkprobleem en productkwaliteitsverloop:

- Het opnemen van een ruwe schatting van productkwaliteit in een logistiek netwerkprobleem garandeert niet dat producten aan klanten worden geleverd met voldoende kwaliteit. Verschillende factoren rondom productkwaliteit moeten worden meegenomen, zoals de mate van kwaliteitsverval, de variabiliteit in productkwaliteit en minimale kwaliteitseisen van klanten. Dit verhoogt niet alleen de kans dat de daadwerkelijk geleverde kwaliteit in overeenstemming is met de gevraagde kwaliteit, maar het verhoogt ook de leversnelheid en leverbetrouwbaarheid.
- Het meenemen van productkwaliteitsverloop in logistiek netwerkontwerp of -configuratie zorgt voor een betrouwbaarder en winstgevender netwerk. Echter, met het aantal logistieke handelingen in de keten neemt ook de uitdaging toe om goed om te gaan met kwaliteitsverloop.
- Waar het ontwerp en de configuratie van een logistiek netwerk voor generieke producten afhangt van de afstanden en volumes in het netwerk, hangt het ontwerp en de configuratie van een logistiek netwerk voor bederfelijke producten vooral af van de mogelijkheden en obstakels om kwaliteitsverlies te beperken.

De volgende inzichten zijn verkregen betreffende de interactie tussen het systeem en het type model:

- Het integreren van netwerkontwerp en netwerkbesturings-problemen vergroot de dynamiek in het netwerk. Dit maakt het noodzakelijk om een hybride optimalisatie en simulatie aanpak te gebruiken voor het oplossen van het geïntegreerde probleem.
- Voor het ontwerpen en configureren van een logistiek netwerk voor bederfelijke producten is een hybride optimalisatie en simulatie aanpak nodig om echt grip te krijgen op productkwaliteitsverloop.
- Een hybride optimalisatie en simulatie-aanpak moet het detail niveau van de productkwaliteit-modellering in het optimalisatiemodel aansturen, omdat meer detail de runtime significant vergroot terwijl het niet noodzakelijkerwijs bijdraagt aan het vinden van de beste logistieke netwerkconfiguratie.
- Een hybride optimalisatie en simulatie-aanpak is afhankelijk van de specifieke probleem-setting, meer dan een zuiver optimalisatiemodel.

Concluderend, het grip krijgen op de dynamiek en onzekerheid in de duur van logistieke handelingen, in productkwaliteit en in product kwantiteit door het inzetten van een hybride optimalisatie en simulatie aanpak, zorgt voor een logistieke netwerkconfiguratie die geschikt is voor het op tijd leveren van producten met de juiste kwaliteit.

Management inzichten

Discussies binnen het DaVinc^{3}i project, omtrent de resultaten vanuit het onderzoek in dit proefschrift, hebben gezorgd voor een gevoel van urgentie bij sectorpartners om de configuratie van het logistieke netwerk tegen het licht te houden. De kostenvoordelen tot 28% geven een duidelijke stimulans om een hub netwerk te ontwerpen. De configuratie van het netwerk moet daarbij worden afgestemd op het type keten. Verschillende voorbeelden hebben sectorpartners aangespoord om na te denken over de vraag of hun logistieke netwerk nog past bij hun huidige keten. Ze heroverwegen de functie van bestaande locaties en bekijken of bestaande locaties kunnen worden samengevoegd, gesloten of verplaatst. Het onderzoek in dit proefschrift ondersteunt de sierteeltsector in de transitie van een aanbod-gestuurd naar een vraag-gedreven ketennetwerk, waarbij rekening gehouden wordt met verschillen in producten en markten en afwegingen tussen kosten, responsiviteit en productkwaliteit.

Het onderzoek in dit proefschrift laat zien dat een logistiek hub netwerk moet worden ontworpen op Europese schaal. Door het grote aandeel van het midden- en kleinbedrijf in de sierteeltsector is het te verwachten dat samenwerking moet worden gezocht om het volume bij elkaar te krijgen dat nodig is om een hub netwerk te rechtvaardigen. Als de productstromen met een lange afstand tussen herkomst en bestemming leidend zijn bij het ontwerp van het hub netwerk en als rekening wordt gehouden met de bederfelijkheid van de producten, dan kan een collectief, winstgevend en betrouwbaar netwerk ontstaan. De haalbaarheid van een hub netwerk kan worden versterkt als schattingen van productkwaliteit door het netwerk heen worden ingezet om de prijs voor de uiteindelijke klant te bepalen.

Discussie en verder onderzoek

Een bespreking van het onderzoek geeft aanleiding tot suggesties voor verder onderzoek, wat samengevat is als:

- Binnen het veld van SCM voor levensmiddelen en verse producten is er nog altijd weinig aandacht voor individuele productkarakteristieken en de relatie van die karakteristieken met logistieke activiteiten. Het onderzoek in dit proefschrift heeft zicht gericht op een specifieke productkarakteristiek, bederfelijkheid, door het modelleren van productkwaliteitsverloop voor verschillende producten.
- In het onderzoek voor dit proefschrift zijn logistieke en kwaliteitsverloop-modellen gecombineerd. In toekomstig onderzoek kan worden gekeken naar de gevoeligheid van de ontwikkelde modellen voor het gebruikte kwaliteitsverloop-model.
- De integratie van zowel voorraad-allocatie als proces-allocatie heeft gezorgd voor een gezamenlijke optimalisatie van netwerkontwerp en klantorder-ontkoppelpunten, wat de netwerkconfiguratie ten goede komt. Toekomstig onderzoek kan de integratie van strategische en tactische beslissingen verder uitbreiden door ook operationele beslissingen te integreren, vooral omdat bederfelijkheid van producten specifiek tot uiting komt op operationeel niveau.
- Dit proefschrift laat een opbouw zien naar een hybride optimalisatie en simulatie aanpak. Er zijn verschillende manieren om optimalisatie en simulatiemodellen te combineren. In toekomstig onderzoek kan worden gekeken naar verschillende combinaties van optimalisatie en simulatie om te analyseren welke combinatie in welke probleem-setting het beste past.
- Er is een substantiële vooruitgang in de ontwikkeling van stochastische optimalisatiemodellen en optimalisatiemodellen waar dynamische factoren in zijn meegenomen. Toekomstig onderzoek kan gericht zijn op het ontwikkelen van optimalisatiemodellen die om kunnen gaan met zowel stochastische als dynamische factoren en die ook binnen een redelijke tijd grote problemen kunnen oplossen.
- De inzichten die zijn verkregen in dit proefschrift kunnen ook worden gebruikt om ketennetwerken anders dan het sierteeltnetwerk te ondersteunen, bijvoorbeeld voor voedingsmiddelen, energie, medicijnen, chemicaliën en bio-raffinaderij producten. Toekomstig onderzoek kan zicht richten op een combinatie van sectoren die elkaar aanvullen om zo de haalbaarheid van een logistiek hub netwerk te vergroten.

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About the author

Marlies de Keizer was born on November 7, 1979 in Dordrecht (The Netherlands). In 1998, she started her studies at the faculty of Economics and Business Administration, Tilburg University. Halfway through her studies, Marlies was a board member of study association Tilburgse Econometristen Vereniging and the Wim Bogers Foundation. In 2004, she graduated cum laude for the doctoral programme in Econometrics and Operational Research.

After graduation, Marlies started her working career at TNO Mobility and Logistics. She is furthermore trained as a software developer at Sogeti and Charta Software. After 7 years of working in industry, Marlies returned to the university and started her doctoral program within the DaVinc^{3}i project. She got to know the floricultural sector and visited many growers, traders and logistics service providers. This enabled her to link her theoretical quests with practical issues. As part of her doctoral program she attended courses at WUR, at the Dutch Network on Mathematics of Operations Research (LNMB) and at a doctoral MIT-Zaragoza Summer School at Zaragoza Logistics Center (Spain). She attended a number of scientific conferences (11th EurOMA Doctoral Seminar, 39th conference on The mathematics of operations research organized by LNMB, 26th European Conference on Operational Research, 13th International Symposium On Locational Decisions) and was awarded a 2012 INFORMS Simulation Society Winter Simulation Conference travel award. Marlies furthermore stayed at TUM School of Management, Technische Universität München, for three months.

Completed training and supervision plan

Marlies de Keizer
Wageningen School of Social Sciences (WASS)

Name of the learning activity	Department/ Institute	Year	ECTS (1=28 hrs)
A) Project related competences (managing your own research project)			
Food Supply Chain Management	WASS	2011	2.5
Randomized algorithms	LNMB	2011	1.0
Heuristic methods in Operations Research	MasterMath	2011	6.0
Summer academy course: Supply Chain Inventory Systems	MIT/Zaragoza Logistics Center	2011	2.5
Summer academy course: Environmental Considerations in Managerial Decision-Making	MIT/Zaragoza Logistics Center	2011	2.5
Logistics & Freight Transport System Analysis	TRAIL Research School	2011	2.0
Dinalog Winterschool	Dinalog	2012	1.5
Stochastic Programming	Ärhus University	2013	5.0

Continued on next page

Name of the learning activity	Department/ Institute	Year	ECTS (1=28 hrs)
B) General research related competences (becoming a broad academic)			
Introduction course	WASS	2011	1.0
Writing research proposal	WUR	2011	4.0
Information Literacy including EndNote Introduction	WGS	2011	0.6
Techniques for Writing and Presenting a Scientific Paper	WGS	2012	1.2
C) Career related competences (personal development and your own future)			
Mobilising your –scientific- network	WGS	2012	1.0
Voice and presentation skills	Voice Matters	2012	0.5
‘Perishable product supply chain network design’	WASS PhD day	2012	1.0
‘Hybrid simulation and optimization approach to design and control fresh product networks’	Winter Simulation Conference	2012	2.0
‘Process and inventory allocation in a perishable product logistics network’	LNMB	2014	2.0
Supervision of bachelor and master students	WUR	2011-2014	2.0
Total			**38.3**

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