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HYBRID SIMULATION AND OPTIMIZATION APPROACH TO DESIGN AND CONTROL FRESH PRODUCT NETWORKS

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ABSTRACT

This paper discusses and typifies logistics decision making in a highly complex system, namely an international fresh product supply chain network. Taking the floricultural sector as example case, we develop a conceptual model that incorporates the important system characteristics (e.g. network design, inventories), context factors (e.g. demand and supply uncertainty, perishability) and performance indicators (e.g. costs and responsiveness). We review literature and present quantitative modeling techniques that are used to design, plan and control a supply chain network. Given an assessment on the suitability of modeling techniques for specific characteristics of fresh products, we present a hybrid simulation and optimization modeling approach for the design and control of a fresh product supply chain network.

1 INTRODUCTION

Traditionally Supply Chain Management was concerned with improving the efficiency of supply chains. This perspective broadened in at least two dimensions. First, the supply chain scope extended to a network scope, and even a global network scope. This implies substantial geographical distances, leading to increased transportation costs and lead-times, which complicates decisions concerning the trade-off between transportation and inventory costs (Meixell and Gargeya 2005). Second, the efficiency objective extended to lean and agile objectives. This implies that not only costs are to be controlled but also speed of product flows. These developments are also reflected in Fresh product Supply Chain Networks (FSCN), where a trade-off between transportation and inventory costs is even more complex due to the perishable nature of fresh products.

FSCNs also have more specific characteristics. External factors like weather related variability in product availability and quality, and demand and price variability, complicate the management of FSCNs as compared to more general SCNs (Ahumada and Villalobos 2009). Aggravated by the global scope, supply and demand uncertainty is high, where uncertainty is related to product quantity as well as product quality, origin and timing. When it comes to FSCN objectives, the control of product quality throughout the network should be taken into account (Akkerman, Farahani, and Grunow 2010). The perishability of fresh products, i.e. a limited shelf life or a decreasing value of the product, makes them vulnerable to environmental conditions during transport and handling, and affects whether the product is fresh enough when delivered to the customer. This also relates to responsiveness, i.e. being able to deliver products in the right quantity at the right time and place with the right quality, a significant objective for FSCNs (van der Vorst, Tromp, and van der Zee 2009).

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The developments and characteristics for FSCNs on the one hand lead to a design issue, i.e. determining functions and location of facilities; and on the other hand to a control issue, i.e. managing product flows and stocks. When modeling these issues, one needs a stochastic approach to incorporate uncertainties and a dynamic approach to incorporate quality decay and responsiveness. Our aim is to determine and describe a suitable combined stochastic and dynamic modeling approach for designing and controlling a Fresh product Supply Chain Network.

The remainder of this article is organized as follows. In the next section we will give a review of literature reviews in the field of quantitative modeling techniques with a Supply Chain Management perspective. Then we will describe the characteristics of an FSCN and construct a conceptual model for FSCN design and control. In this, the floricultural sector is taken as an example of a fresh product supply chain network to validate the conceptual model. Using the characteristic elements of the conceptual model we will judge the modeling techniques on their suitability to design and control a responsive FSCN, resulting in a hybrid simulation and optimization approach. At the end we will summarize our conceptual work and give an outlook on how we will materialize it in future research.

2 LITERATURE REVIEW

The aim of our literature review is to get an overview of decision problems within and of quantitative modeling techniques used for FSCNs. Due to the limited number of reviews that specifically address FSCNs and quantitative modeling techniques, we broadened our search to Supply Chain Management (SCM). We restricted the search to reviews that are published in 2005 and later, so that we cover literature published in the last 20 years. We searched in Scopus using terms “supply chain management”, “quantitative”, “simulation”, “operations research”, “mathematical”, “analytical” and “optimization”. Based on a reference and citation analysis we created a collection of 18 reviews, of which 3 are FSCN reviews (Amorim et al. 2011; Ahumada and Villalobos 2009; Akkerman, Farahani, and Grunow 2010). As a summary, the years that the reviews cover (only shown for the last 20 years) and the journals they are published in are shown in Figure 1.

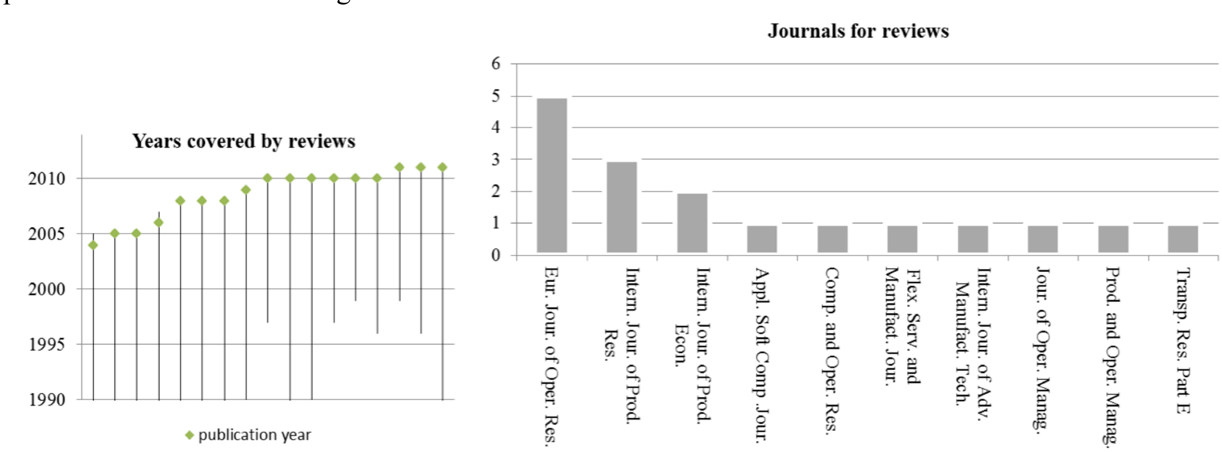

Figure 1: Overview of review papers on quantitative modeling in SCM

In the reviews we encountered different types of SCM problems at different decision levels being addressed with quantitative techniques. We differentiate the decision problems between design, control and integrated design and control. We mean by these categories:

- Design
  Evaluation of different strategies like efficiency and agility; determining customer order decoupling points; supply chain network design: strategic decisions regarding the number and location of production facilities, the amount of capacity at each facility, the assignment of each market re-

gion to one or more locations, and supplier selection for sub-assemblies, components and materials (Chopra and Meindl 2007); coordination: analyzing decision making patterns and communication between individual actors (Chan and Chan 2009).

- Control
  Supply chain planning: coordinated planning of individual actors in a way that optimizes the value of the overall supply chain (Kouvelis, Chambers, and Wang 2006); demand management: balances the customers' requirements with the capabilities of the supply chain, the process is not limited to forecasting, it includes synchronizing supply and demand, increasing flexibility, and reducing variability (Lambert, García-Dastugue, and Croxton 2005); inventory management: determining inventory policies (ordering, issuing, etc.) for raw materials, work in process, and finished goods (Chopra and Meindl 2007); production and distribution planning: planning problems in the production process (scheduling, lot sizing, assignment, etc.) and distribution process (vehicle routing, final goods replenishment, etc.) (Amorim et al. 2011).
- Design and control
  Jointly optimizing and analyzing design and control decisions, e.g. location-inventory problems or location-routing problems.

Looking at the modeling techniques discussed in the reviews, we can make distinctions between optimization and simulation techniques, between static and dynamic techniques and between deterministic and stochastic techniques. Based on this we define seven categories (we want to asses different quantitative modeling techniques, so we do not incorporate algorithmic techniques like heuristics in our review, nor do we take into account data analysis techniques, numerical studies or techniques like Pareto fronts and game theory):

- Mathematical optimization: e.g. linear programming, mixed integer linear programming.
- Stochastic optimization: e.g. stochastic programming, robust programming.
- Dynamic optimization: e.g. dynamic programming, classic control theory.
- Stochastic dynamic optimization: e.g. stochastic dynamic programming, robust control theory, stochastic control theory.
- Static simulation (no distinction between deterministic and stochastic, most simulation techniques have similar deterministic and stochastic variants): e.g. Monte Carlo simulation.
- Dynamic simulation (no distinction between deterministic and stochastic, most simulation techniques have similar deterministic and stochastic variants): e.g. discrete event simulation, system dynamics, petri net simulation.
- Hybrid optimization and simulation: e.g. mixed integer linear programming and discrete event simulation, control theory and system dynamics.

The obvious advantage of optimization is that it finds an optimal solution, but the downside of this is that the solution times increase exponentially in problem size. Moreover, variance and dynamics can only be handled to some extent. In contrast, simulation is very well suited to mimic dynamic systems and to incorporate stochastic elements, but a simulation will not give a decisive solution. It will give estimates for system indicators under certain system settings, with a risk that too much trust is put in these estimates.

Using the categorizations of decision problems and quantitative techniques we can assess which combinations appear in the reviews. As a result we come to the overview as given in Table 1. It gives an indication for the suitability of problems and techniques, and possible research gaps.

The major decision problem in the reviews is supply chain network design. This used to be focused on finding the optimal design in a deterministic setting, which explains the large contribution of mathematical modeling. However, simulating techniques are emerging to study the robustness and sensitivity of designs to dynamism in input parameters. Planning at individual links (i.e. scheduling, lot sizing, etc.) and in a supply chain perspective are also notable decision problems. Mathematical modeling is very well suited for planning in more isolated settings, but the complexity of coordinated planning makes that also simulating techniques are deployed. There are some reviews that mention integrated problems, like inventory-routing problems, but most of them are within the control category. There are only two reviews that mention problems that integrate design and control, for which the authors use mathematical optimization.

Although not directly visible from Table 1, we can deduce that mathematical techniques are more concerned with design decisions, while simulating techniques are more concerned with control decisions. The dynamics of supply chain management especially come into view at the more detailed levels of control, which explains the use of techniques that can handle stochastic and dynamic systems. Subsequently, one would expect that the combination of design and control decisions would be tackled by a combination of mathematical and simulation techniques, but this does not show.

Table 1: SCM decision problems and quantitative modeling techniques

		Decision problem		
		Design	**Control**	**Design and control**
Modeling technique	**Mathematical optimization**	Gunasekaran and Ngai 2005; Klibi, Martel, and Guitouni 2010; Naim and Gosling 2011; Meixell and Gargeya 2005; Kouvelis, Chambers, and Wang 2006; Chan and Chan 2009	Stadtler 2005; Ahumada and Villalobos 2009; Peidro et al. 2008; Choi and Sethi 2010; Kouvelis, Chambers, and Wang 2006; Amorim et al. 2011; Akkerman, Farahani, and Grunow 2010	Melo, Nickel, and Saldanha-da-Gama 2009; Akkerman, Farahani, and Grunow 2010
	Stochastic optimization	Peidro et al. 2008; Ko, Tiwari, and Mehnen 2010; Kouvelis, Chambers, and Wang 2006; Klibi, Martel, and Guitouni 2010	Ahumada and Villalobos 2009; Peidro et al. 2008; Ko, Tiwari, and Mehnen 2010	
	Dynamic optimization	Gunasekaran and Ngai 2005; Arzu Akyuz and Erman Erkan 2009; Chan and Chan 2009	Sarimveis et al. 2008; Ahumada and Villalobos 2009; Choi and Sethi 2010; Ko, Tiwari, and Mehnen 2010	
	Stochastic dynamic optimization	Meixell and Gargeya 2005	Sarimveis et al. 2008; Ahumada and Villalobos 2009; Peidro et al. 2008; Akkerman, Farahani, and Grunow 2010	
	Static simulation	Jahangirian et al. 2010	Jahangirian et al. 2010	
	Dynamic simulation	Gunasekaran and Ngai 2005; Peidro et al. 2008; Naim and Gosling 2011; Zhang, Lu, and Wu 2011; Chan and Chan 2009; Choi and Sethi 2010; Jahangirian et al. 2010; Akkerman, Farahani, and Grunow 2010	Sarimveis et al. 2008; Ahumada and Villalobos 2009; Peidro et al. 2008; Zhang, Lu, and Wu 2011; Kouvelis, Chambers, and Wang 2006; Jahangirian et al. 2010; Akkerman, Farahani, and Grunow 2010	
	Hybrid optimization and simulation	Peidro et al. 2008; Arzu Akyuz and Erman Erkan 2009; Jahangirian et al. 2010	Peidro et al. 2008; Zhang, Lu, and Wu 2011; Jahangirian et al. 2010	

In Table 2 we summarize suggestions for further research from the reviews. It reveals a difference in focus for the first two FSCN reviews and the more general SCN reviews. The special concern in fresh produce supply chains related to product quality and supply uncertainty has stimulated research on tracing products with RFID, gathering information on lead-time and product quality, and using this for dynamic control. This also calls for a need to incorporate perishability and quality decay modeling in network control. Another issue for FSCN is the integration of models. On the one hand, there is a need to extend the work on integrating production and distribution planning. On the other hand, there is a need to extend the incorporation of product quality decay modeling from network control to network design. More general SCN reviews especially mention different types of uncertainties (e.g. in customer demands, lead times and production fluctuations) to be taken into account in network control and design, thereby integrating or selecting the right uncertainties. Regarding objectives more emphasis should be given to a revenue perspective instead of a cost perspective and including responsiveness. The use of lead-time information for dynamic control is also suggested in SCN reviews. Concerning techniques especially hybrid modeling is mentioned, e.g. integrating petri nets with other tools, integrating soft computing with more practical algorithms, combining analytical modeling with simulation, etc. Jahangirian et al. (2010) argue that this popularity can be attributed to the need for models that can cover the mutual impacts of different organization parts with different structures.

Table 2: Suggestions for further research from reviews

		Amorim et al. 2011	Akkerman, Farahani, and Grunow 2010	Ahumada and Villalobos 2009	Zhang, Lu, and Wu 2011	Peidro et al. 2008	Chan and Chan 2009	Gunasekaran and Ngai 2005	Melo, Nickel, and Saldanha-da-Gama 2009	Klibi, Martel, and Guitouni 2010	Meixell and Gargeya 2005	Naim and Gosling 2011	Arzu Akyuz and Erman Erkan 2009	Choi and Sethi 2010	Ko, Tiwari, and Mehnen 2010	Sarimveis et al. 2008	Kouvelis, Chambers, and Wang 2006	Jahangirian et al. 2010	Stadtler 2005
Network design	*Incorporating uncertainty*				x	x	x	x	x	x									
	Incorporating perishability																		
Network control	*Incorporating uncertainty*				x	x													
	Incorporating perishability	x	x	x															
	Using lead time information for dynamic control							x						x	x	x	x		
	Using product quality information for dynamic control	x	x																
Integration	*Within network control*	x		x															
	Network design and control		x						x										
Objective	*Costs*								x	x	x	x	x						
	Responsiveness									x		x	x	x					
	Product quality	x										x							
Hybrid modeling					x	x	x								x			x	

2.1 Conceptual Model

When shifting from a traditional supply chain to a virtual responsive supply chain, supply chain network reconfiguration or redesign is a notable issue (Ho, Au, and Newton 2003). In Figure 2 we depict our conceptual model to point out the concepts that we are considering in this matter. A critical part are the facility location decisions (Melo, Nickel, and Saldanha-da-Gama 2009), and related to this the decision of which flows to allocate to which facilities. It creates a blueprint for a hub network and can be used to determine the position of the Customer Order Decoupling Point (CODP), which is the point that separates 'the part of the organization oriented towards customer orders from the part of the organization based on planning' (Hoekstra and Romme 1992). The CODP should be determined for every product-market combination, hence a supply chain can have multiple CODPs, which induce the process allocation (i.e. where to execute which activity). The part of the organization that is based on planning, i.e. upstream the CODP, is characterized by make-to-stock processing which creates inventories that prepare the supply chain for fluctuations in demand or supply. Facilitated by new conditioning technologies it will be possible to allocate inventories for fresh products to strategic locations within the network. Although the primary concern of FSCNs is to deliver good quality products, there is always a trade-off between costs/efficiency and product quality.

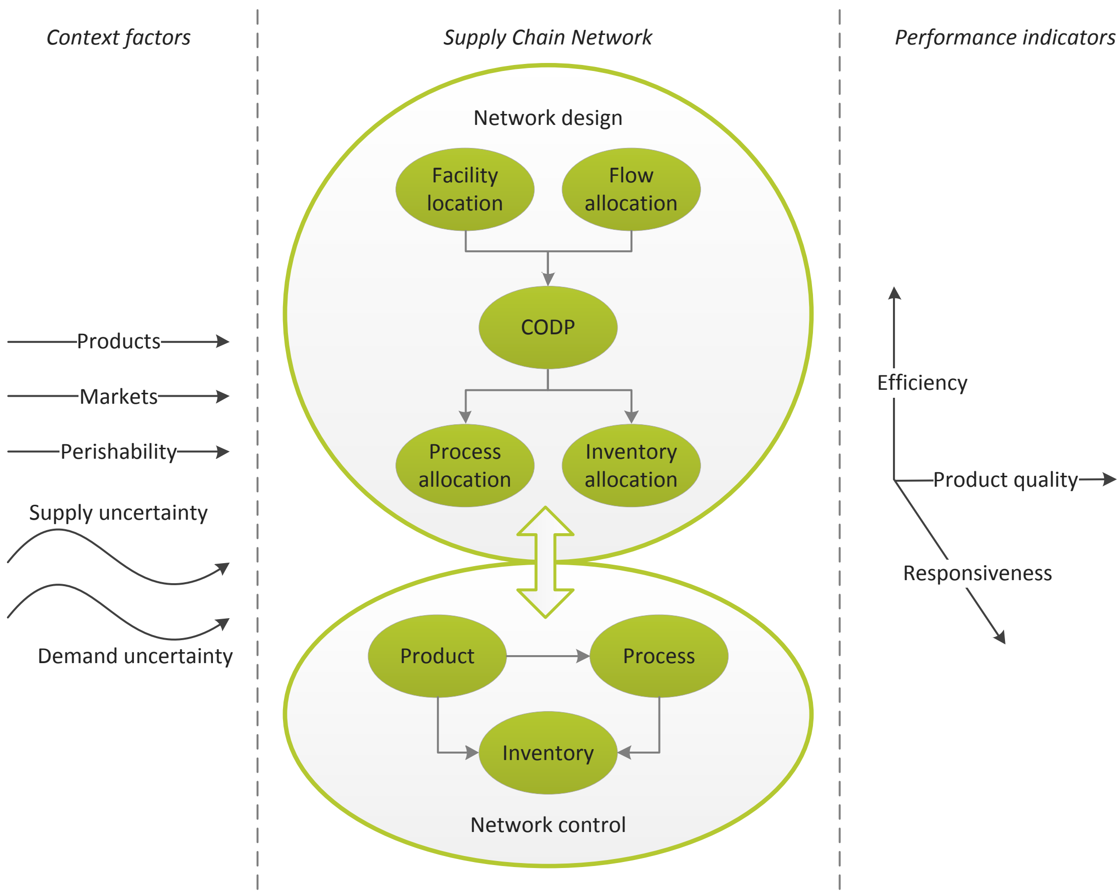

Figure 2: Conceptual model of FSCN design and control concepts

The characteristic demand and supply uncertainties of FSCNs can be taken into account at a high level in strategic design decisions, but especially the operational consequences for network control are of interest. When demand and supply get revealed the products flow through the network, undergoing processes on their routes from grower to outlet, while increasing and decreasing inventories. But what happens with product flows when supply is disrupted? Or when stocked products go bad? Also, when supply and demand uncertainty increases, flows tend to get smaller and more diverse. It creates a need for the supply chain network to be responsive (Reichhart and Holweg 2007), which we denote as being able to accurately respond to a customer order and deliver the right product in the right quantity at the right time and place.

It is clear that, for fresh products, perishability and the trade-off between responsiveness, efficiency and product quality is to be regarded in network design and control.

2.2 Floricultural Sector

To underpin our conceptual work we analyzed the floricultural supply chain network. This network delivers two types of products, i.e. potted plants and cut flowers, to two types of markets, i.e. a specialized channel denoted as detail (e.g. flower shop, market), and an unspecialized channel denoted as retail (e.g. supermarket, construction market). Virtual stores are still very rare in floriculture and therefore they are not considered in our analysis for now.

An overview of differences between cut flowers and potted plants is given in Table 3. The sourcing areas for example are much more global for cut flowers than for potted plants, effecting the location of facilities. Furthermore, cut flowers are combined into a bouquet, which puts demands on the processes executed at facilities. The overview also shows that there are different types and levels of perishability. This can have different influences on the possible locations, the distances between the locations, the opportunities for flow, process and inventory allocation, etc.

The most important market characteristics that influence the network design and control are listed in Table 4. Different sales channels have different characteristics and requirements, e.g. (1) there is a large amount of specialized flower shops that carry a large variety of products as opposed to the small amount of construction markets that offer a limited variety; (2) retail orders large amounts well in advance while street markets want to order few products today for today's selling; (3) flower shops demand a high quality product and supermarkets want to be able to guarantee a vase life of seven days. These examples show the importance of the location of facilities in relation to the location of outlets, the inventory that is held at the facilities, the processes that customize the products to outlet demand, etc.

Table 3: Characteristics for different product types

	Cut flowers	**Potted plants**
Sourcing	Global: Netherlands, Israel, Kenya, South-Africa, Colombia, Spain	European: Denmark, Belgium, USA, France Upcoming: Poland, East-Germany
Sales market	European: Germany, United Kingdom, France, Italy, Belgium	European (local-for-local): Germany, France, Italy, United Kingdom, Belgium
Key sales channel	Detail	Retail
Type of product	Compound product (bouquet)	Single product
Perishability	Lose 15% of value per day	Under optimal conditions almost non-perishable
Quality attribute(s)	Vase life: time between production and packaging of the product and the point at which it becomes unacceptable under defined environmental conditions (Luning and Marcelis 2009)	Height, number of stems per pot, number flowers per stem, etc.
Key trade mechanism	Auction clock	Direct trade
Network type	Supply driven	Demand driven

Due to the strong clutch of commerce and logistics in the floricultural sector, a lot of the products that go into Europe flow through the market places in the Netherlands. With virtualization physical flows can be decoupled from information and commercial flows (DAVINC3I 2010), which creates new opportunities for designing and controlling the network. It implies that internationally sourced flowers and plants can flow through a logistics network which expands the current Dutch network into Europe leading to a responsive supply chain delivering high quality products to differentiated market segments.

Another development is the use of conditioned containers within the floricultural supply chain network, especially in sea transport. Inside these reefer containers one can control environmental conditions and hence control deterioration of flowers and plants transported and stored in them. It entails that it is still possible to deliver good quality products with prolonged logistical activities. It allows for larger lead-time and flexibility of logistical activities in the supply chain, which again creates new opportunities for designing and controlling the network.

Table 4: Characteristics and requirements for different sales channels

	Detail	**Retail**
Number of shops	Large	Small
Product variety	Large	Limited
Type of product	Specialized	Mass-customized
Order size	Small	Large
Order lead time (time between placing and receiving an order)	Day	Week(s)
Quality	High	Guaranteed

3 HYBRID SIMULATION AND OPTIMIZATION APPROACH

The conceptual model presented in section 2.1 shows that we are looking at a network design problem in combination with a network control problem. Generally, a network design problem can be very well tackled by mathematical optimization, as can be seen in the modeling overview of section 2. In this, dynamic and stochastic elements, like perishability and demand and supply uncertainty, can only be incorporated at a long time scale and a rough product flow level. And even then it will complicate the problem hugely. The network control problem is in itself already a complex dynamic system due to different sources, markets and products demanding different processes. Incorporating perishability and supply and demand uncertainty at this operational level further increases the stochastic and dynamic nature of the network control. Especially evaluating the responsiveness of an FSCN and keeping track of product quality throughout the FSCN asks for techniques that can handle dynamic elements on a small time scale and detailed product level. Simulation is well suited for these dynamics. Finally, as a multi-objective goal the trade-off between efficiency, product quality and responsiveness complicates the design and control.

Combining the advantages of both mathematical optimization and simulation we propose a hybrid approach for the integrated network design and control problem. In Figure 3 we depict the main structure of our hybrid simulation and optimization approach.

1. The starting point is a scenario, which describes the setting for the supply chain network, i.e. products and markets, supply and demand uncertainties, perishability aspects li006Be environmental conditions during transport and handling, etc.; and the parameters for the supply chain network, i.e. transport and location costs, and product quality and responsiveness requirements.
2. The scenario is fed into the network design module, which mathematically determines the location of facilities and allocation of product flows, processes and inventories. The aim of this module is to design an optimal network with respect to costs and with imposed restrictions for product quality and responsiveness requirements on a high abstract level.
3. The design is then passed to the network evaluation module, which is a discrete event simulation that mimics the course of events in logistics.

4. A local search loop is used to find the optimal operational design in the neighbourhood of the initial design.
5. The simulation subsequently uses different network control modules, e.g. for inventory or transport. The aim of the control modules is to determine control actions, which can be done by simple decision rules or sophisticated (optimization) models. The simulation invokes the product decay module to determine product quality based on environmental conditions.
6. The overall aim of the simulation is to evaluate the network design and control on costs, responsiveness and product quality on a detailed level.
7. Information gathered with the evaluation module is looped back to the scenario generation module. Based on the evaluation, the scenario generation module will set up a new scenario with updated parameters which starts a new iteration of design and control optimization.
8. The iterations are continued until a stopping criterion is reached.

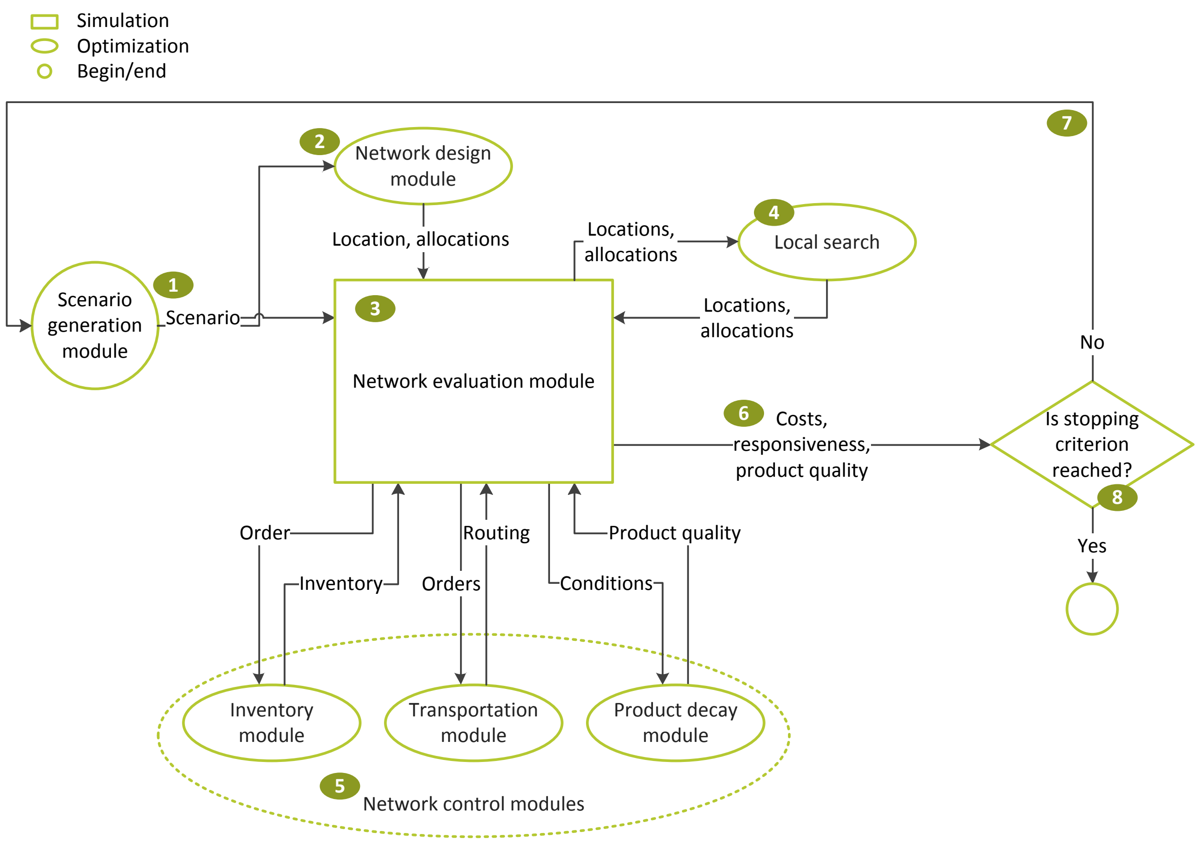

Figure 3: Hybrid simulation and optimization approach

We have chosen a modular approach to allow us to easily add and upgrade modules. A network design module and a product decay module are already available.

4 CONCLUSION AND FURTHER RESEARCH

In this paper we presented a hybrid simulation and optimization approach for solving a design and control problem in Fresh product Supply Chain Networks (FSCNs). The approach is based on a literature study of 17 papers which review quantitative modeling of SCM decision problems, and on a conceptual model of FSCN design and control concepts. The conceptual model takes into account requirements that are specific to FSCNs. That is, perishability of fresh products demands a responsive network that operates efficiently while maintaining product quality as much as possible.

From the literature study we conclude that a hybrid optimization and simulation approach for an integrated design and control problem fills a research gap (see Table 1). Although hybrid approaches are found in some reviews and integrated design and control problems are found in (Melo, Nickel, and Saldanha-da-Gama 2009), none of the reviews reports on solving an integrated problem by a hybrid approach. Hybrid approaches are used for problems with characteristics given in the conceptual model, e.g. a few papers take into account both supply and demand uncertainty (Peidro et al. 2008), or use a multi-objective approach (Zhang, Lu, and Wu 2011). However, no papers are reported in the reviews that describe a hybrid approach which takes into account perishability. There is a need, and a challenge, to incorporate the deterioration of product quality in both design and control models. Simulation is a powerful technique to model detailed product characteristics as well as logistical control processes. Optimization techniques are able to produce new network scenarios and to optimize the flow of products throughout the network. A hybrid approach combining simulation and optimization is a promising research direction.

The conceptual model in section 2.1 has been illustrated using the floricultural sector. In further research we will implement the hybrid simulation and optimization approach and set up a floricultural case study to test the hybrid approach and to analyze different supply chain network designs and controls and their effects on efficiency, responsiveness and product quality.

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