Chapter 1

Introduction

1.1 Motivation

Increasing globalization and vertical disintegration have resulted in a large increase of transportation volumes. One of the industries that has undergone a radical change is the chemical industry. During the last decade, many companies of this industry have established global production sites and use these sites to fulfill global demands. Bayer [11], for instance, plans to invest 1.8 billion USD into a Toluylen-Diisocyanat (TDI) production site in Shanghai by 2009, doubling the production capacity of this site to 300,000 tons per year. The output of this plant is used to fulfill worldwide demands. Similar investments have been made by many other companies. BASF [8] expanded the capacity of its plants in Nanjing, Ludwigshafen, Antwerp, and Pasir Gudang throughout the years 2002-2006 and opened a new plant in Pudong in 2006. SABIC [72], [73], the Saudi Basic Industries Corporation, a leading manufacturer of chemicals, fertilizers, plastics, and metals, expanded its global network by acquiring, amongst others, the petrochemicals business of the Dutch group DSM (2002), Huntsman's UK petrochemical activities (2006), and GE Plastics' US-based activities (2006). In 2006, SABIC shipped over 8.6 million metric tons of chemicals and gases to more than 90 ports in over 35 countries around the world with nearly 500 vessels.

To match global demand with global supply, chemical companies use global supply chains. Typically, products are produced at a few plants and are shipped to regional tank farms, where they are stored. Customer demand is then fulfilled from these regional tank farms. In most situations, the tanks are owned by a tank farm operator that rents the tanks to chemical companies.

When designing a supply chain, companies must make a number of decisions: They must decide on the product mix and production quantities at the production sites, on the locations of the tank farms and tank capacities to use, and on the frequency of deliveries between plants. We provide a comprehensive deterministic model and solution methodologies, taking into consideration all these factors and using realistic (i.e., non-linear) cost structures.

Another major challenge for the design of supply chains arises from the abundance of risks and uncertainty encountered in reality. In the chemical industry, where our real-life problem is based, demand fluctuations in the past two centuries have been substantial. Average annual demand fluctuation can be quantified by the coefficient of variation, i.e. the absolute standard deviation relative to the mean demand. For example, China had an average annual variation of 78% between 1989 and 2007. For Ireland it was 76% and for India 52%. Table 1.1 gives an overview of the average annual variation of chemical sales per country for the years 1989-2007.

Country	**Average sales** USD billion	**Annual variation** percent	**Country**	**Average sales** USD billion	**Annual variation** percent
China	142.1	78	Canada	32.0	31
Ireland	3.1	76	USA	425.6	28
India	37.8	52	Netherlands	22.6	28
Russia	39.8	43	Sweden	11.7	27
Korea	55.3	41	Singapore	6.1	27
Mexico	29.2	40	France	77.7	25
Brazil	53.1	37	UK	67.0	24
Spain	41.7	36	Belgium	21.6	22
Australia	19.0	35	Italy	77.1	22
Taiwan	34.0	34	Germany	120.9	21
Switzerland	14.8	34	Japan	208.2	10

Source: ABIQUIM, ANIQ, CCPA, CEFIC, JCIA, VCI, Bureau of the Census, Eurostat, Statistics Canada, United Nations, WTO, American Chemistry Council estimates

Table 1.1: Chemical sales and annual variation per country, 1989-2007

These industry examples underline how immanent stochasticity is in the world today and the importance of considering it in supply chain design. Most existing approaches for stochastic supply chain design only consider 2-echelon supply chains with direct delivery from plants to customers and linear cost. These simplifying assumptions make the models computationally tractable, but might be unrealistic for many real-life companies. We provide a complex stochastic model considering realistic supply chain characteristics (e.g., non-linear cost structures, large scale problems) and develop efficient solution methodologies.

While it is most favorable to already consider stochasticity in the design phase of a supply chain, many supply chains exist today that were designed based on historic data and thus might not optimally serve today's or tomorrow's needs. Many supply chains today put strong emphasis on exploiting labor cost advantages in low cost countries. The cost savings from manufacturing in these countries are substantial and in many cases by far offset the additional transport costs incurred. However, considering imminent changes in markets today (e.g., oil prices, CO_2 emission regulations, wage levels), it is not clear whether these supply chain structures designed mainly around offshoring possibilities will be ideal in the future. Supply chain practitioners require an indication of what plausible future factor cost developments are and how these will affect their supply chains so they can prepare to adapt their supply chains to the changed circumstances. We provide this information, analyzing probable factor cost developments and their impact on supply chain structures.

Our work is based on a project for a chemical company that redesigned its sea freight supply chain and we base our numerical analyses on data of this company. However, the application of the models and the solution approaches is not limited to this setting. They can also be used for designing supply chains in other industries that exhibit similar characteristics as the chemical industry, such as the coal, metal, stone, oil, and gas industries. The general techniques, albeit with an adapted model, can be applied to many further industries as well.

1.2 Supply chain setup

We now introduce the general supply chain structure that we use for all the approaches presented in this book. Only the mathematical formulation changes depending on whether we have a deterministic or a stochastic setting. We consider a supply chain where plants i can produce products p that can be shipped via potential tank farm locations j to serve the demand of customers k (Figure 1.1).

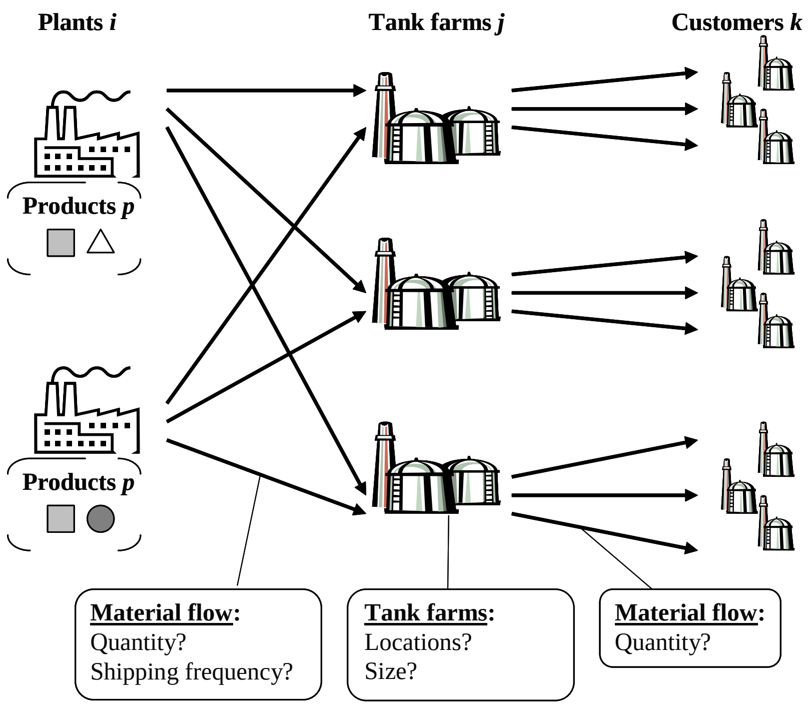

Figure 1.1: Schematic supply chain structure

In the application that motivated our research, the tank farms are supplied by plants via sea transport, where the transportation cost between plants and tank farms is highly non-linear. The products are then stored in the tanks of the tank farms. The unit rental cost of large tanks is much less than the unit rental cost of small tanks, i.e., the storage cost is highly non-linear. Customers are supplied from tank farms via regional sea freight operators that experience economies of scale in terms of fixed cost degression, albeit with constant cost factors.

In our model, we will use the notion of a transport schedule t. The transport schedule is an index that specifies the frequency at which a tank farm is served from a plant. It is important to include frequencies already in the strategic planning of the supply chain in order to correctly evaluate economies of scale and required tank sizes. Failing to incorporate these factors can lead to suboptimal supply chain designs, as we will show in Section 3.4.1. In theory, more than one schedule could be used for a product along a certain route. However, in practice we find that it is generally optimal to choose one schedule in order to exploit economies of scale.

The cost structure of chemical supply chains exhibits several important economies of scale that have to be considered when designing the supply chain. The most important ones are economies of scale in transportation quantities and economies of scale in tank capacities. The freight rate between Rotterdam and Buenos Aires, for instance, decreases from about 400 USD/m^3 to 200 USD/m^3 when the transportation volume increases from 1,000 m^3 to 10,000 m^3. The cost of tank rental exhibits similar economies of scale. The rental cost of a typical 500 m^3 tank, for instance, is 54 USD/m^3/year, whereas the cost of a 2,000 m^3 tank is only 24 USD/m^3/year. Figures 1.2 and 1.3 show examples for typical transport cost and tank rental cost functions of the company. It is important to consider these economies of scale for supply chain design since they can have substantial impact on the network structure and the size of the rented tanks.

We now introduce the general method we use to model these piecewise linear cost functions in mixed-integer form. This methodology was first proposed by Balakrishnan and Graves [7]. Cost factors vary depending on quantity q, e.g., if more is shipped a lower unit cost applies. The piecewise linear cost function is defined by fixed costs F_n, variable costs V_n, and breakpoints in the cost function occurring at quantities B_n, where $B_0 = 0 < B_1 < B_2 < ... < B_N$. The index n refers to the cost level. Let $Z(q)$ be the total cost. Figure 1.4 shows how the piecewise linear cost function is modeled.

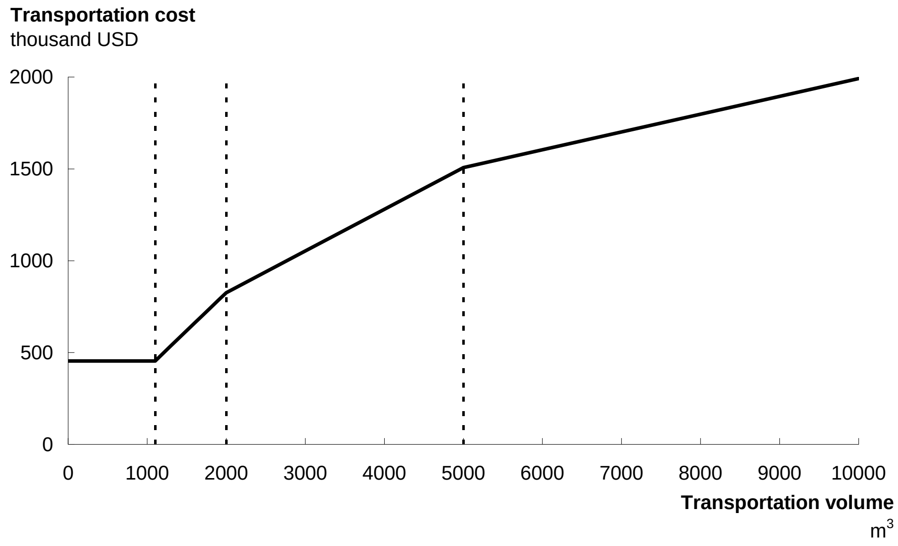

Figure 1.2: Transportation cost between Rotterdam and Buenos Aires

The cost function can thus be defined as

$$Z(q) = \begin{cases} F_n + V_n q & \text{if } B_{n-1} < q \leq B_n \quad \forall n \\ 0 & \text{otherwise} \end{cases} \tag{1.1}$$

We now show how we formulate the function as a mixed-integer program. We use q_n to denote the quantity shipped at cost level n, i.e.,

$$q_n = \begin{cases} q & \text{if } B_{n-1} < q \leq B_n \\ 0 & \text{otherwise} \end{cases} \quad \forall n. \tag{1.2}$$

x_n is a binary variable that represents the decision to open or close the respective route, warehouse, etc. at cost level n, i.e.,

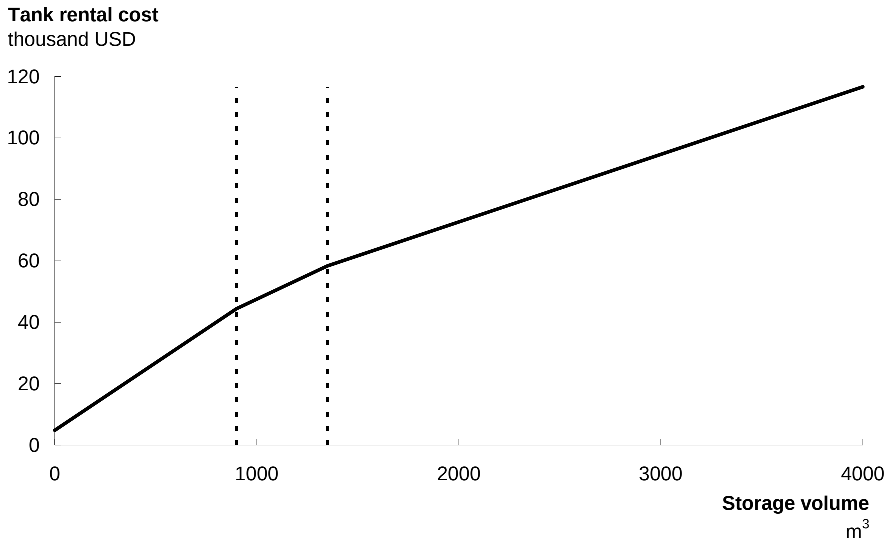

Figure 1.3: Tank rental cost in the harbor of Durban

$$x_n = \begin{cases} 1 & \text{if } q_n > 0 \\ 0 & \text{otherwise} \end{cases} \quad \forall n. \tag{1.3}$$

The mixed integer model that results for a given quantity q is

$$Z(q) = \sum_n (F_n x_n + V_n q_n), \tag{1.4}$$

$$\sum_n q_n = q, \tag{1.5}$$

$$\sum_n x_n \leq 1, \tag{1.6}$$

$$q_n \leq x_n B_n \quad \forall n, \tag{1.7}$$

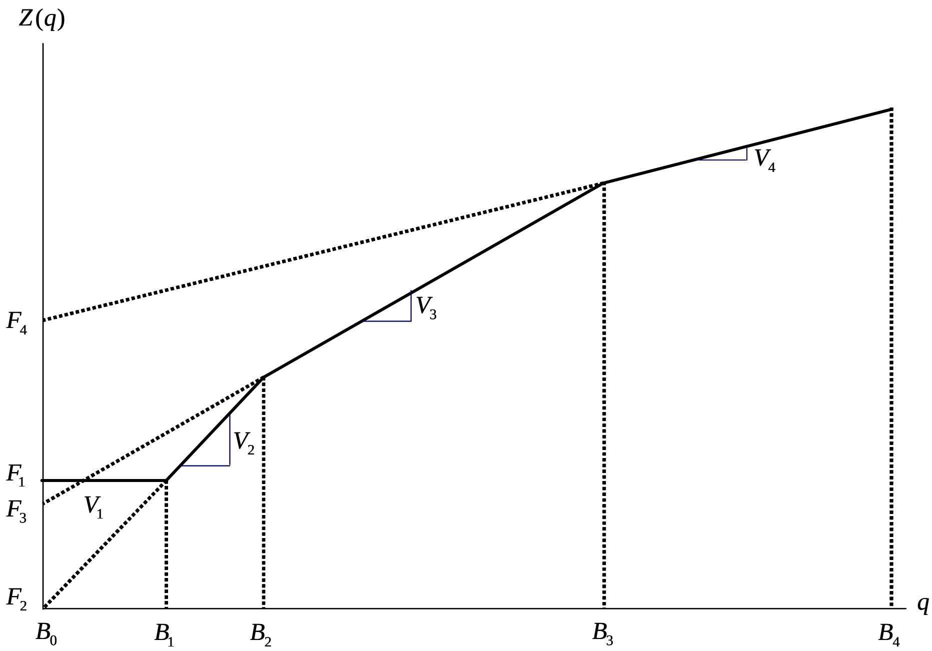

Figure 1.4: Modeling technique for piecewise linear functions

$$q_n \geq x_n B_{n-1} \quad \forall n, \tag{1.8}$$

$$q_n \geq 0 \quad \forall n, \tag{1.9}$$

$$x_n \in \{0, 1\} \quad \forall n. \tag{1.10}$$

Function (1.4) calculates the cost for a piecewise linear cost structure depending on the volume. Constraint (1.5) states that the total quantity q needs to be distributed amongst different cost levels n by assigning portions of this quantity q to different q_n. The cost level essentially specifies which piecewise linear part of the cost curve is used and depends on the volume. Constraint (1.6) states that at maximum one x_n may be set equal to 1. For functions that continuously exhibit economies of scale, this constraint is not necessary because it is always more favorable to pool volumes in order to capture economies of scale. Constraint (1.7) states that the quantity assigned to q_n may not exceed the upper bound B_n of the cost function for the respective cost level n. Similarly, Constraint (1.8) states that the quantity may not be lower than the lower bound B_{n-1} of the cost function for the respective cost level n. (1.8) is only necessary for non-concave functions. For concave functions, it is never optimal to select a cost level lower than n for quantities in the range of cost level n. Constraints (1.7) and (1.8) also force the x_n that corresponds to the $q_n > 0$ to be set to 1. Constraints (1.9) - (1.10) are standard non-negativity and integrality constraints. This model formulation for piecewise linear functions automatically assigns the volume to the correct portion of the cost function. We will base all the transformations to mixed integer form of the piecewise linear functions in our models on this method.

We base all our computations on real data from a chemical company that redesigned its supply chain under the circumstances described in this thesis. The company operates 4 plants, uses 35 potential tank farms, serves 57 customer locations, and offers 38 products. Figure 1.5 gives an overview of the relevant locations.

1.3 Outline

The remainder of this thesis is organized as follows. In Chapter 2, we give an overview of relevant literature. In Chapter 3, we develop a deterministic supply chain design approach. In Chapter 4, we extend the approach to the design of

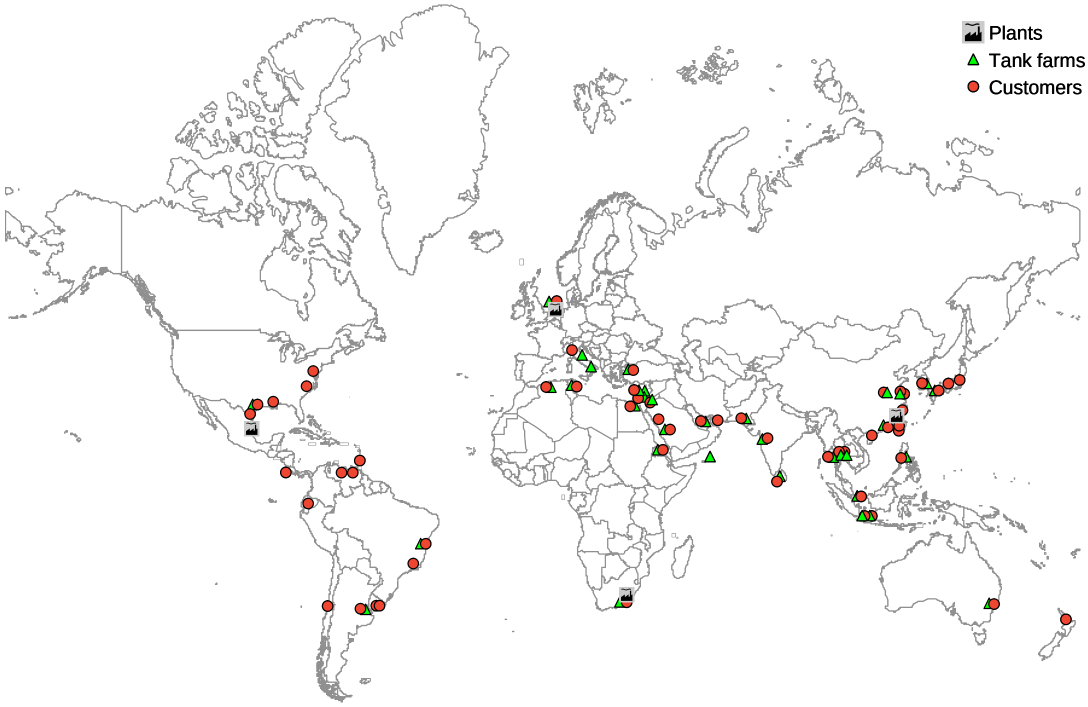

Figure 1.5: Overview of locations of real-life supply chain

stochastic supply chains. In Chapter 5, we analyze future factor cost developments and their impact on existing supply chains. Finally, in Chapter 6, we conclude. We now give a brief overview of the content of each chapter. Note that we designed each chapter so that it can be read on its own, with a comprehensive introduction of the mathematical model and methods used.

Chapter 2 This chapter summarizes the literature relevant to our work. We begin by describing work on deterministic supply chain design models. We distinguish between models with non-linear storage cost, models with non-linear transport cost, and models with both non-linear storage and transport cost. We see that, while subsets of the relevant supply chain characteristics have been considered, no approach exists that incorporates all relevant factors in one model. We continue with stochastic supply chain design models. We classify the literature by solution approach, distinguishing between semi-deterministic, scenario modeling, and probabilistic approaches. Our review shows that most stochastic models focus on small (i.e. 2-stage) supply chains with linear cost structures. Finally, we look at other attempts besides stochastic supply chain design that have been made at dealing with risk. We review work on risk identification, evaluation, and management in supply chains, e.g. through flexibilization. We see that rather theoretic models prevail, while attempts to actually quantify the risk for existing real world supply chains and the impact these will have on their setup are missing.

Chapter 3 In this chapter, we consider a 3-echelon, multi-product supply chain design model with economies of scale in transport and warehousing that explicitly takes transport frequencies into consideration. Our model simultaneously optimizes locations and sizes of tank farms, material flows, and transport frequencies within the network. We consider all relevant costs: product cost, transport cost, tank rental cost, tank throughput cost, and inventory cost. The problem is based on a real-life example from a chemical company. We show that considering economies of scale and transport frequencies in the design stage is crucial and failing to do so can lead to substantially higher costs than optimal. We solve a wide variety of problems with branch-and-bound and with the efficient solution heuristics based on iterative linearization techniques we develop. We show that the heuristics are superior to the standard branch-and-bound technique for large problems like the one of the chemical company that motivated our research.

Chapter 4 In this chapter, we develop stochastic supply chain design approaches for a large scope of multi-echelon problems based on a the same real-life situation faced by the chemical company. We consider all relevant costs - product cost, transport cost, warehousing cost, and inventory cost. Transport and warehousing costs exhibit economies of scale and are highly non-linear. We consider transport frequencies already in the design phase in order to accurately evaluate costs. We develop a structured sampling approach based on orthogonal arrays. We show that this approach leads to substantially better supply chain designs than unstructured randomized scenario generation techniques and deterministic approaches. We perform tests for various demand volatilities and show that the value of our approach increases in demand volatility. We also show that significant savings can be achieved by increasing supply chain flexibility.

Chapter 5 In this chapter, we analyze two typical chemical supply chains to show how factor cost developments can affect these supply chains in the future. We regard a supply chain for low value, labor unintensive chemicals and one for high value, labor intensive chemicals. We analyze 36 different scenarios with different combinations of oil price and wage level developments. We show how factor costs influence the optimal supply chain in terms of network structure, inventory and delivery policy, and regional production split and shipments amongst regions. Our results show that these factor costs can have a substantial influence on the optimal supply chain structure. It is thus imperative that supply chain practitioners prepare for these imminent changes now.

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