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Development of a decision support tool for supply network planning: A case study from the chemical industry

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Abstract For the practical use of supply chain management powerful planning tools are needed to support production and logistics decisions at various planning levels. In our paper, we focus on medium-term supply network planning. As a real application, the production of a chemical additive in a multi-site production and distribution network is considered. Supply network planning is an exceedingly complex task which can only be accomplished with the support of computer based systems. Instead of using an off-the-shelf planning tool, the company decided to develop its own linear programming based optimization model. This model allows the consideration of various application features, e.g. the use of alternate production resources or the generation of electrical energy as a side product. The optimization model has proven to be of major value for both strategic and operational decisions. The model is now in full use at three production-distribution networks in different parts of the world.

Keywords Production and distribution planning; Supply network management; Linear programming model; chemical industry

1 Introduction

In the chemical industry in particular in the production of chemical commodities, highly capital-intensive production facilities are used to produce a variety of output products in a large volume. While production facilities are concentrated at specific sites, customer locations are scattered over different countries and economic regions. Traditionally, customer locations are aggregated into zones and assigned to one chemical plant from where the requested final products are shipped. However, due to seasonal fluctuations in demand and short-term variations of customer order sizes, many companies in the chemical industry have pooled their production and distribution resources in order to shorten replenishment times for the fulfillment of customer orders, reduce safety stocks, and improve the utilization of the production facilities. This way, considerable savings in production, inventory holding and distribution costs can be gained.

On the other hand, through the establishment of supply networks with multiple production sites, there is a strong need to coordinate the activities of the various decision making units in the network, in particular, to allocate demand among the production sites, to choose the most economical production mode of the chemical processes, and to organize the value adding activities in the network (cf. Kannegiesser et al. 2009). The need for an improved coordination of supply network activities gives rise for the application of quantitative decision support tools, primarily linear programming models, which offer the possibility to integrate production and distribution planning and to sub-ordinate the respective decisions under one unique objective function (cf. Günther and van Beek 2003). At the same time, the linear programming framework provides the flexibility to model application-specific features which are essential in the chemical industry.

In this paper, we consider the production of a chemical additive in a multi-site network. Planning and control of this kind of networks is an exceedingly complex task which can only be accomplished with the support of computer based systems. The company at hand first intended to use an off-the-shelf planning tool for supply chain management. At that time, however, the newly introduced “Advanced Planning Systems” did not provide open interfaces which allowed the integration of external modules needed to model the particularities of the chemical processes. One such issue was the production of energy from a gas that was achieved in large quantities as a side product from the chemical processes. Therefore, the company decided to develop its own linear programming based optimization model.

The remainder of the article is organized as follows. The next section gives a brief overview of production planning and scheduling issues which arise in the chemical industry in the context of supply chain management. In Section 3, the linear optimization model developed for the case study application is presented. In the final section, conclusions are drawn and the practical use of the presented optimization model is discussed.

2 Production planning and scheduling in process industry

Principally, production systems can be classified into discrete parts manufacturing and process industry related systems. In discrete parts manufacturing, countable objects are produced, modified, or assembled in a sequence of mechanical production steps. Process industry, however, is not well-defined in literature. Its major characteristic is the dominance of chemical or biological production technology through which substances are extracted, transformed, purified, and mixed. Industry segments belonging to process industry are chemical and pharmaceutical production, food processing, paper and metal production, and crude oil processing among others. In this paper, we focus on chemical production as the major segment of process industry.

In contrast to other industries, production sites in the chemical industry contain several infrastructure units, e.g. utility plants and waste treatment facilities (cf. Hübner 2007). Often different facilities are combined at one manufacturing site. For instance, one facility produces the main product and secondary facilities are established to process side-products. This is also the case in the considered industrial application, where a gaseous side-product is converted into different kinds of energy.

Production technology to be found in the chemical industry includes *multi-purpose batch plants*, which are used to produce a broad range of products with flexible equipment configurations, *dedicated plants*, which are designed for the production of only a single product type in a small range of specifications, and *multi-product plants*, which produce a broad range of product variants from basically the same processing steps. The latter type of plant is found in the industrial application considered in this paper.

To reduce the complexity of the entire planning process, planning activities in the context of supply chain management can be decomposed into several hierarchical levels. At the highest level, the *strategic network design* is defined including the location of plants and their capacities, the choice of the production technology and the product portfolio for each plant in the network (cf. Hübner and Günther 2007). At the intermediate level of *supply network planning*, the focus is on the allocation of external demand between plants, the adjustment of production capacity in response to seasonal demand fluctuations, the choice of chemical production modes and equipment configurations, and the transfer of products within the network including the shipment of final products to customers (cf. Grunow et al. 2002 and 2003). Finally, at the lowest level *operational planning and scheduling* takes place which defines the assignment of production tasks to equipment units, the stepwise execution of the production process including changeovers between different chemical processing conditions and recipes, as well as the assignment of product-specific storage devices (cf. Blömer and Günther 2000).

In the chemical industry, the complexity of detailed production scheduling is determined by such factors as variable campaign sizes, networked material flows, the production of side-products which is often unavoidable due to the nature of the underlying chemical processes, mixing and blending processes, sequence and usage dependent cleaning operations, finite intermediate storage, and flexible equipment configurations. In this paper, we deal with supply network planning for a specialty chemical. Hence, the detailed scheduling of the chemical processes is not included in the optimization model.

3 Supply network model

3.1 Application environment

The company considered is one of the world-largest producer of specialty chemicals and represented with subsidiaries, plants, and sales organizations all over the world. From the many chemical products, we consider one specific additive which is used by a number of large-sized industrial customers in various countries. Every year, the company headquarters and the key customers negotiate contracts in which the yearly supply volume and other conditions, like sales price and delivery terms, are established. However, customers are free to define their replenishment quantities on short-notice. Though the annual demand volume for the entire production network is known in advance, short-term demand figures show seasonal variations which can be predicted by adequate forecasting techniques, e.g. by Winters' seasonal forecasting method.

One issue of considerable practical importance are the differences in the specifications of a chemical product, even of the same type, resulting from the individual processing equipment at the various plants and raw materials obtained from local sources. Although these differences are very minor, they play an important role in the customer's manufacturing processes where the chemical substance is used as an additive to improve the performance of the final products. Hence, in order to avoid frequent adjustments of the processing conditions, customers have approved a limited number of chemical plants from which they are supplied with the chemical additive. These approvals have to be considered as an important constraint in the allocation of demand volume between the chemical production sites in the network.

The principal structure of the chemical process (see Figure 1) is the same in all production sites. The main product is produced in a variety of about 100 specifications from a number of feeds through a multi-stage continuous production process. The output is stored in product-specific silos which are used as a buffer between the production process and the shipment to customers. Besides the main product, a gaseous side-product is produced in large quantities. Because in most countries it is illegal to bleed off this gas, the company utilizes special facilities for the transmission of the gaseous side-product into different forms of energy, like electrical energy and long-distance heat. This energy output is bought up by local energy suppliers on a long-term contractual basis with defined minimum and maximum quantities per month. Apart from the transmission of gas into energy for supply to the external market, part of the side-product is used as an internal energy supply in the thermal chemical production process.

The company's main concern in mid-term supply network planning is the allocation of customer demand quantities to the approved production sites, the determination of the transportation quantities between the plants and the customer locations, and decisions on the use of the gaseous side-product. In the following sub-section, a linear optimization model is developed to support these decisions.

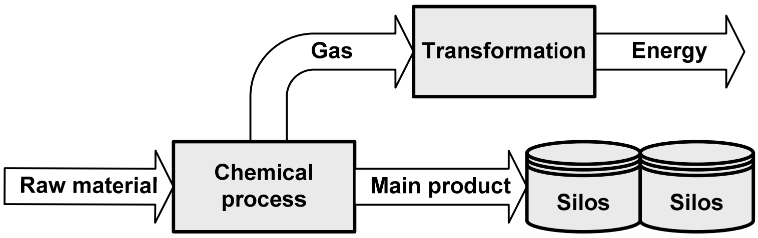

Figure 1: Structure of the chemical process

3.2 Mathematical model

Before the mathematical optimization model is developed, we define the required notation.

Indices and sets

$c \in C$	customers
$i \in I$	products
$j \in J(i)$	production variants (packaging types) of product i
$k \in K$	energy types produced
$s \in S$	production sites
$(s,c,i) \in A$	approvals: production sites s which are feasible for supply of customer c with product i
$l \in L(s)$	production lines in production site s

Parameters

TC_{scij}	transportation cost per unit of variant j of product i shipped from site s to customer c
PC_{silt}	production cost per unit of product i produced in site s on line$l$ in period t
HC_{si}	inventory holding cost per unit of product i per period in site s
SP_{skt}	sales price per unit of energy type k generated in site s in period t
D_{cij}	annual demand of customer c for variant j of product i
d_{cijt}	share of annual demand of customer c for variant j of product i ordered in period t (based on forecasts)
$\bar{S}_{ci}$	maximum number of sites which supply customer c with product i
SC_{sit}	storage capacity of product i at site s in period t
o_{sil}	output per hour of product i on line l at site s
OT_{slt}	number of operation hours of line l at site s in period t
Q_s	minimum total sales quantity of site s
p_s	throughput of the energy transformation equipment per hour at site s
PT_{st}	number of operation hours of the energy transformation equipment at site s in period t
α_{sil}	quantity of the gaseous side product achieved per unit of product i on line l at site s
γ_{sil}	energy value per unit of the side product achieved per unit of product i on line l at site s
λ_{sk}	degree of efficiency in the transformation process of energy type k at site s
E_{skt}, $\bar{E}_{skt}$	minimum and maximum quantity of energy type k at site s in period t, respectively

Decision variables

$x_{silt} \geq 0$	quantity of product i produced in site s on line l in period t
$u_{scijt} \geq 0$	quantity of variant j of product i shipped from site s to customer c in period t
$U_{sci} \in \{0,1\}$	=1, if site s supplies customer c with product i (=0, otherwise)
$v_{skt} \geq 0$	quantity of energy type k generated in site s in period t
$V_{sk} \in \{0,1\}$	=1, if energy type k is generated in site s
$y_{sit} \geq 0$	inventory of product i in site s at the end of period t

The objective function aims to minimize total production, transportation and inventory holding costs. Revenues from energy sales are maximized and thus considered with a negative sign in the objective function.

$$\begin{aligned} \text{Min} \sum_{t\in T}\sum_{s\in S}\sum_{c\in C}\sum_{i\in I}\sum_{j\in J(i)} TC_{scij}\cdot u_{scijt} + \sum_{t\in T}\sum_{s\in S}\sum_{i\in I}\sum_{l\in L(s)} PC_{silt}\cdot x_{silt} + \\ \sum_{t\in T}\sum_{s\in S}\sum_{i\in I} HC_{si}\cdot y_{sit} - \sum_{t\in T}\sum_{s\in S}\sum_{k\in K} SP_{skt}\cdot v_{skt} \end{aligned} \tag{1}$$

Constraints to be considered are the following.

Demand coverage: The total transportation quantity from all approved sites must cover the forecasted replenishment quantity of each customer.

$$\sum_{s \in \{s' \in S | (s',c,i) \in A\}} u_{scijt} \geq D_{cij} \cdot d_{cijt} \qquad \forall c \in C, i \in I, j \in J(i), t \in T \tag{2}$$

Approvals: Transportation quantities are only allowed to take positive values if the customer is assigned to the site for supply with a specific product.

$$u_{scijt} \leq D_{cij} \cdot U_{sci} \qquad \forall (s,c,i) \in A, j \in J(i), t \in T \tag{3}$$

Maximum number of suppliers: For each product-customer combination the number of supplying sites is limited.

$$\sum_{s \in \{s' \in S | (s',c,i) \in A\}} U_{sci} \leq \bar{S}_{ci} \qquad \forall c \in C, i \in I \tag{4}$$

Inventory balances: The ending inventory of a product at a site is determined by the inventory at the beginning of the period, the production quantities on the different lines at the site, and the quantities shipped to the customers. Moreover, the total inventory of each (unpacked) product is limited due to storage capacity constraints.

$$y_{sit} = y_{s,i,t-1} + \sum_{l \in L(s)} x_{silt} - \sum_{c \in \{c' \in C | s,c',i) \in A\}} \sum_{j \in J(i)} u_{scijt} \qquad \forall s \in S, i \in I, t \in T \tag{5}$$

$$y_{sit} \leq SC_{sit} \qquad \forall s \in S, i \in I, t \in T \tag{6}$$

Production capacity: The available operation time of each equipment unit must be observed.

$$\sum_{i \in I} \sum_{l \in L(s)} x_{silt} / o_{sil} \leq OT_{slt} \qquad \forall s \in S, t \in T \tag{7}$$

Minimum sales quantity per site: For each site a minimum total sales quantity has to be ensured.

$$\sum_{c \in \{c' \in C | s,c',i) \in A\}} \sum_{i \in I} \sum_{j \in J(i)} \sum_{t \in T} u_{scijt} \geq_{s} \qquad \forall s \in S \tag{8}$$

Capacity of the energy transformation equipment: The available operation time of each equipment unit must be observed.

$$\sum_{i \in I} \sum_{l \in L(s)} \alpha_{sil} \cdot x_{silt} \leq p_s \cdot PT_{st} \qquad \forall s \in S, t \in T \tag{9}$$

Energy balance: The energy value of the side product quantities must be equal to the energy value of the generated energy taking the degree of efficiency in the transformation process into account.

$$\sum_{i \in I} \sum_{l \in L(s)} \gamma_{sil} \cdot \alpha_{sil} \cdot x_{silt} = 3600 \cdot \sum_{k \in K} v_{skt} / \lambda_{sk} \qquad \forall s \in S, t \in T \qquad (10)$$

Minimum and maximum energy sales quantities: If a specific energy type is produced at a site, minimum and maximum sales quantities must be observed due to contracts with local energy suppliers.

$$\underline{E}_{skt} \cdot V_{sk} \leq v_{skt} \leq \bar{E}_{skt} \cdot V_{sk} \qquad \forall s \in S, k \in K, t \in T \qquad (11)$$

4 Conclusions

The optimization model presented in the previous section has been introduced for operational planning at a global chemical company. To implement the model, CPLEX and OPL Studio have been used as standard optimization packages. The model is linked to a data base which holds the company-internal data. User-friendly graphical interfaces allow the planners to run the model with alternate input data and to evaluate different scenarios.

The model is now in full use at three production-distribution networks in different parts of the world. Besides its role as operational planning tool, the optimization model is widely used for scenario analyses. For instance, the impact of reduced or increased production capacities at specific sites was evaluated. Other issues of considerable practical importance in the respective business unit are the increase in raw material prices and possible expansions of the energy transformation facilities. So far, the optimization model has proven to be of major value for both strategic and operational decisions.

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