Supply Network Planning and Plant Scheduling in the Chemical-Pharmaceutical Industry - A Case Study Investigation

Gang Yang[1], Martin Grunow[2], and Hans-Otto Guenther[3]

TU Berlin,Germany[1,2,3], g.yang@pm-berlin.net[1], m.grunow@pm-berlin.net[2], ho.guenther@pm-berlin.net[3]

ABSTRACT

In the chemical-pharmaceutical industry, production stages are often assigned to different locations, even different countries. A key issue is the co-ordination of campaign schedules at different production stages in the various plants. In practice, it is almost impossible to determine exact optimal solutions to the corresponding complex supply network problem with respect to overall logistics costs. Hence, a two-stage hierarchical modelling approach is suggested. At the upper level, campaign schedules are determined for the entire supply network. At the lower level, detailed production schedules are derived for each plant. At this stage, the specific requirements of production equipment and other types of resources are considered according to the recipes of the particular chemical process. The applicability of the approach suggested is investigated using a case study from industry.

INTRODUCTION

To produce high value-added pharmaceuticals, major European enterprises tend to build up multi-national supply networks with plants located in different countries. This development is primarily motivated by the legal and taxation systems in different countries and financial incentives for investments in economically low developed regions. Because of the small transportation volume of high-value active ingredients, transportation costs of products are of minor relevance. However, transit times between different plants need to be considered.

Supply networks are particularly complex in the production of active ingredients, where numerous material flows between different production locations occur resulting in cumulative lead-times of up to two years. As a consequence, effective inter-plant co-ordination of production activities within the entire supply network is of utmost importance in order to avoid unnecessary inventories, inefficient capacity utilisation, and uneconomical allocation of resources.

In recent years, supply network planning emerged as one of the most challenging problems in chemical process industry, especially when multi-stage production systems and multi-purpose equipment are used (e.g. Berning et al. 2002; Timpe and Kallrath 2000). A large body of literature on production planning and logistics in the process industry has evolved over the last two decades. For the problem at hand, the relevant literature can be classified into three groups: *strategic network design*, *supply network planning*, and *batch scheduling*. For a detailed review we refer to Grunow et al. (2003) and Kallrath (2002). This classification reflects the hierarchical structure, which is typical of today's advanced planning and scheduling systems applied in many enterprises in the chemical and pharmaceutical industry (see e.g. Günther and van Beek, 2003).

CASE STUDY PROBLEM

As a case study, the production of active ingredients is considered. Due to the chemical peculiarity in processing active ingredients, production is carried out in batch mode, which offers the advantage of an increased flexibility with respect to product variety, production volume and the range of recipes that can be processed by the particular equipment (e.g. Blömer and Günther 2000; Grunow et al. 2003). However, production planning and scheduling is significantly complicated by the large number of stages and batches involved, the dissimilarity of the production paths, and short-term variations in product demand. Since multi-purpose equipment is employed, clean-out of equipment units is required when changing to another product type.

Figure 1 shows the entire production network which is characterised by the large number of production stages involved and the customer-supplier relationships between the plants. For some of the products, the production process involves three or four different plants in several countries. (In Figure 1, the various plants are indicated by different shadings of grey.) Raw materials are transformed into final products (active ingredients) through a number of production stages, so-called manufacturing pipelines. A pipeline consists of multiple stages in which various intermediates are processed and, finally, one or more types of active ingredients are obtained. A pipeline may have a divergent or convergent material flow structure.

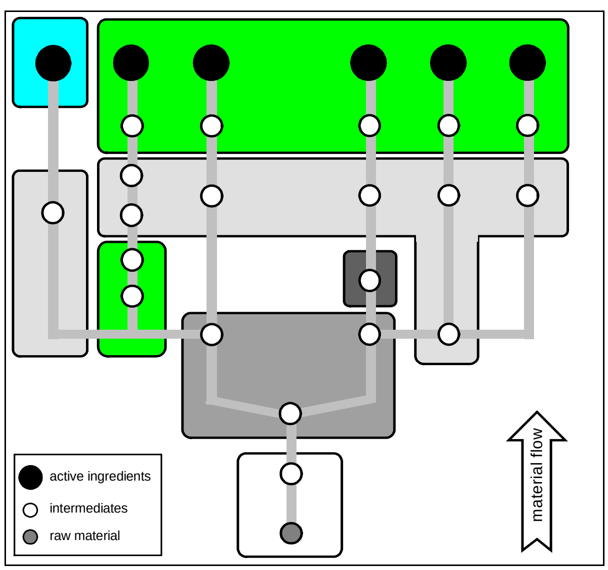

Fig. 1: Example of manufacturing pipelines and corresponding plants

The supply network under consideration is characterized by customer-supplier relationships between plants. For some high-volume products, the entire production process involves three or four different plants in several countries. In particular, supply network planning has to fulfill the following requirements.

- The demand of all final products has to be satisfied without backordering. The size (number of batches) and the sequence of the various campaigns within a plant as well as their starting and finish times have to be determined accordingly.
- The production plans of all plants have to be coordinated, i.e. the entire consolidated production plan must be feasible with respect to the quantities of material available from the predecessor campaigns at upstream plants.
- Specific resource constraints, e.g. the availability of multi-purpose equipment at each plant, must be considered. Thus, the detailed assignment of equipment units to campaigns must be determined. Usually, resource groups are reconfigured after a campaign has been completed.
- The objective is to minimize total logistics costs, including production costs, inventory costs for final products, transportation costs for intermediates and costs for set-up and clean-out operations.

HIERACHICAL MODELING APPROACH

In order to model the production environment with respect to the information structure at different planning levels, a hierarchical representation scheme is proposed, which reflects the real world entities from two different points of view, namely an *equipment* and a *process view*. As a result, two different model representations are obtained. The equipment model represents the structure of equipment units employed to transform raw materials through intermediates to final products within a particular production network. The process model represents the production processes to be carried out and the interrelationships between them. In accordance with the required level of detail at different hierarchical levels, the equipment structure and the process structure can be depicted in a more or less detailed manner.

Based on the hierarchical structure of equipment and processes, production planning within a large production network can be divided into three levels. Figure 2 illustrates the architecture of the proposed hierarchical production planning system. At the aggregate planning level, supply network planning is performed. In this stage, an aggregate view of equipment units and chemical processes applies. The objective is to minimize total logistics costs including inventory costs for final products, production costs for intermediates, and transit costs for material flows. At the lower level, detailed production schedules are derived for each plant considering the specific requirements of production equipment and other types of resources according to the recipes of the particular chemical process. At the lowest planning level (not considered in this paper) production activities are monitored and rescheduled, if necessary.

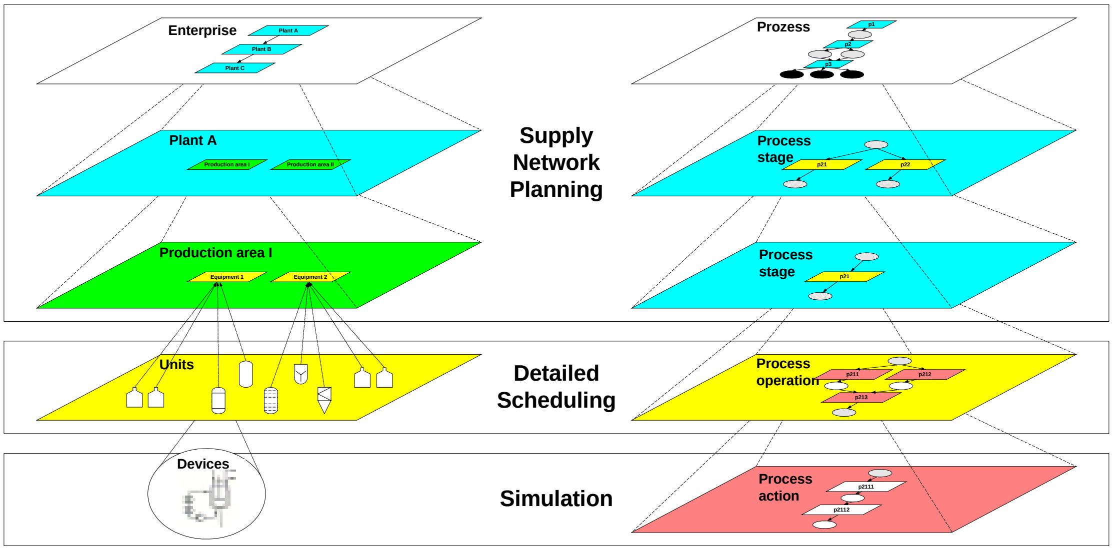

Fig. 2: Architecture of the hierarchical production planning system

Supply network planning

For supply network planning a novel mixed-integer linear programming (MILP) model based on a continuous representation of time is developed. (For details the reader is referred to Grunow et al., 2003.) The MILP model is very efficient in terms of computational tractability. However, an application to an exceptionally large industrial case such as the one investigated here requires the use of adequate aggregation techniques to ensure that computational times are within the limits acceptable for an interactive decision support tool. Hence, four major aggregation techniques are employed. First, consecutive processing tasks, which are required to produce a particular product, are merged into so-called cascades. Second, sub-plants comprising several equipment units are defined in order to reduce the number of decision variables for process-equipment assignments. Third, patterns of material flows between campaigns are introduced which replace individual material flows in the model formulation. Finally, a practical procedure for disaggregating demand data is proposed.

Detailed scheduling

Based on the solution obtained from the aggregate network planning level, earliest release times and due dates for all campaigns producing intermediate products as well as the corresponding material flows are obtained. Within the allowed time windows, local scheduling can be performed at each plant considering a much greater level of detail. In particular, individual equipment units and processing tasks are considered. Taking additional constraints such as renewable resources and sequence-dependent set-up times into account, the size and timing of a campaign may be adjusted. According to the supply relationship defined in the global network schedule, detailed production schedules are obtained by consecutively updating the permissible time-window for each campaign. At this level, we employ a modified model formulation proposed by Méndez et al. (2001). In the industrial application, the plants also produce additional "local" products, which are not incorporated into the multi-plant supply network. According to the company's policy, incorporated into the multi-plant supply network. According to the company's policy, their production is separately scheduled after decisions on the size and the timing of the network-based campaigns have been made. The generated campaign schedule may therefore be used as a basis for making capacity reservations at the local plants.

CONCLUSION

The major disadvantage of a monolithic modelling approach based on a discrete time representation is the huge number of binary variables and constraints when applied to problem instances of realistic dimensions. As a consequence, it is impractical to determine feasible solutions within reasonable computational time even by using powerful computers and efficient optimization software. The proposed hierarchical approach overcomes this difficulty by dividing the decision problem into two stages and by the application of continuous time-based MILP models. The investigation of a real-life application with a planning horizon of 18 months shows that detailed production schedules could be determined in less than 10 minutes of CPU time. A major issue of future research is to integrate the proposed hierarchical modelling approach into an interactive planning system for the chemical process industry.

REFERENCES

Berning, G., Brandenburg, M., Gürsoy, K., Mehta, V., and Tölle, F.-J., "An integrated system solution for supply chain optimization in the chemical process industry," *OR Spectrum*, 24(2002), pp. 371-401

Blömer, F., Günther, H.-O., "LP-based heuristics for scheduling chemical batch processes," *International Journal of Production Research*, 38(2000), pp. 1029-1051

Grunow, M., Günther, H.-O., Yang, G., "Plant co-ordination in pharmaceutics supply networks," *OR Spectrum*, 25(2003), pp. 109-141

Günther, H.O. van Beek, P. (Eds.), "Advanced Planning and Scheduling Solutions in Process Industry," Springer, Berlin et al., 2003

Kallrath, J., "Planning and scheduling in the process industry," *OR Spectrum*, 24(2002), pp. 219-250

Méndez, C., Henning, G. H., Cerdá, J., "An MILP continuous-time approach to short-term scheduling of resource-constrained multistage flowshop batch facilities," *Computers and Chemical Engineering*, 25(2001), pp. 701-711

Timpe, C. H., Kallrath, J., "Optimal planning in large multi-site production networks," *European Journal of Operational Research*, 126(2000), pp. 422-435