OVERVIEW OF PLANNING AND SCHEDULING OF BATCH PROCESS OPERATIONS

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Abstract : Batch production is used for the manufacture of fine chemicals and is particularly appropriate when production quantities are small, or when the procedure or the product demand is likely to change. Batch processes are usually carried out in relatively standard items of equipment whose operating conditions can be adjusted to accommodate a variety of products. Plants for batch operations can be arranged as multiproduct, multipurpose under campaign mode and general multipurpose. In this study, all the three types of batch plants are examined under planning and scheduling. Planning stage is the macrolevel where the problem is outlined and scheduling stage is the microlevel where the production lines are set and the batch sizes determined within the given time horizons to satisfy the product demands. These three problems are examined under different objective functions. *Copyright © 1998 IFAC*

Keywords : Batch Processes, Planning and Scheduling, Multiproduct Plant, Multipurpose Plant

1. INTRODUCTION

Batch processes are commonly used for the production of specialty chemicals such as pharmaceutical, cosmetics, polymers, biochemical, electronic materials, and food products, as they are well suited for producing multiple low-volume, high-value products requiring similar processing paths or complex synthesis procedures. In addition, batch processes offer flexibility in the face of seasonal and fluctuating demands and inexact process knowledge. Batch production will continue to be an important and permanent feature of the Chemical Process Industries.

Between batch and continuous processes when examined under operating costs, given that most low volume products tend to be of high value, aspects such as raw material costs, yields, and product quality control tend to dominate the cost structure of batch processes.

The cost structure of batch processing means that integration techniques need to address a wider problem by considering better scheduling, improved equipment design, and changes in chemistry.

In continuous operations there is :

- one to one correspondence between the recipe steps and the plant equipment items
- the flowsheet is the physical realisation of the recipe and its structure remains fixed in time

On the other hand, in the execution of batch operations:

- the structure of the recipe and the plant equipment network structure are in general distinct
- the equipment configuration may change each time a different product is made
- there exists an additional engineering decision level: the assignment of recipe steps to equipment items over specific intervals of time

In recent years there has been a trend in the domestic chemical industry towards higher priced specialty chemicals. These products are often manufactured in multiproduct facilities designed to produce anywhere from a few to 100 different products. As a result, production scheduling is becoming an important area of chemical engineering.

Scheduling schemes may be classified according to the assumptions made about storage available for partially processed jobs. Intermediate storage assumptions fall into one of four categories :

1. **Unlimited intermediate storage** - any number of intermediates may be stored while awaiting further processing;
2. **Finite intermediate storage** (Papadimitriou and Kanellakis, 1980; Knopf, 1985) - only a finite number of intermediates may be stored while awaiting further processing
3. **No intermediate storage** - the process units serve as a storage. While a unit is storing an intermediate that it has completed processing, further processing is blocked;
4. **No-wait processing** (Reddi and Ramamoorthy, 1972; Wismer, 1972; Van Deman and Baker, 1974; Gupta, 1976) - intermediates must be processed without delay. Under this constraint, job processing is uninterrupted until completion. Total job residence time in the flowshop is the sum of the processing times on the individual process units.

The classification of scheduling based on intermediate storage assumptions is somewhat artificial since some practical present a mixed storage environment. Unlimited intermediate storage may be available to some machines while the no-wait processing condition applies to other segments. No-wait processing is always necessary when intermediate products are unstable.

Production planning and scheduling are intimately linked activities. The production goals set at the planning level depend on marketing considerations but must account for the ability to implement them at the scheduling level. Hence, ideally planning and scheduling should be analysed simultaneously.

The main approach that has been used for the simultaneous treatment of production planning and scheduling is a hierarchical decomposition scheme where the overall planning problem is decomposed into two levels. At the upper level, the planning problem is represented with a multiperiod LP planning model that sets production goals to maximise profit. At the lower level, the scheduling problem is reduced to a sequencing subproblem that must meet the goals set by the planning problem.

Planning is basically a macrolevel problem that is concerned with the allocation of production capacity and time and product inventories, as well as labor and energy resources, so as to determine the production goals that maximise the total profit over an extended period of time into the future. The major objective in production planning is to determine production goals over a specified time horizon given marketing forecasts for prices and product demands and considerations of equipment availability and inventories.

Scheduling is the microlevel problem that is embedded in the production planning problem and that is commonly considered only for a short term horizon. Scheduling involves deciding upon the sequence in which various products should be processed in each equipment so as to meet the production goals that are set by the planning problem. A major objective here is to efficiently utilize the available equipment among the multiple products to be manufactured to an extent necessary to satisfy the production goals.

The scheduling problem involves three closely linked elements :

- assignment of units and resources to tasks
- sequencing of the tasks assigned to specific units
- determination of the start and stop times for the execution of all tasks

The scheduling problem is to :

- determine the order in which tasks use equipment and resources
- the detailed timing of the execution of all tasks so as to optimize plant performance

The below information should be given in a scheduling problem to satisfy the market demands and they are usually determined in the planning stage :

- mode of operation
- product orders
- product recipes
- number and capacity of the various types of existing equipment
- list of equipment types allowed for assignment to each task
- any limitations on shared resources (such utilities or manpower)
- any operating or safety restriction

Extensive reviews in batch processing have been recently reported in the literature (Reklaitis, 1991, 1992). Many of these problems can be posed as mixed integer optimisation problems. A major question in any scheduling algorithm deals with the time domain representation. Kondili et al. (1993a) present a general formulation to the modelling of scheduling problems that arise in batch plants, namely the state task network (STN). The problem is formulated as a MILP model. However the main limitation of the model is the generation of a large number of integer variables and constraints in problems of industrial relevance. Following this work, several techniques were introduced with the objective of reducing the required computational effort. Shah et al. (1993) reformulated the allocation constraints. The uniform discretization of time domain was also applied to parallel flowshop scheduling (Gooding et al., 1993). The simplest sequencing problem is the single machine scheduling. Another important example in the scheduling literature is the general job shop problem (Carlier and Pinson, 1989; Adams et al., 1988). A specialised branch and bound method was developed by Carlier and Pinson (1989) based on one machine scheduling problems. In the context of chemical processing industries, continuous time representations were also developed for the short term scheduling of batch plants. Zentner and Reklaitis (1992) introduced the NUCM (Nonuniform Continuous Time Modelling). The simultaneous planning and scheduling for the case of plants with a single stage and equipment in parallel was studied by Sahinidis and Grossmann (1991). Pinto and Grossmann (1994) considered the case of multiple stages with intermediate storage considerations. The problems were modelled as MINLP's. The problem of scheduling continuous multiproduct plants under resource constraints was studied by Kondili et al. (1993b).

2. BASIC REPRESENTATIONS

A Gantt chart is an equipment occupation diagram in which time is the ordinate and the abscissa has an entry for each equipment item.

Figure 1a shows a Gantt chart for a serial four task recipe in which a distinct unit is assigned to each task. Note that an arrow denotes the transfer of a task output to the next task in the recipe. The cycle time is 6, corresponding to the maximum of the processing times of the four tasks of the recipe. As is typical, several of the units are idle for a considerable portion of the time, but at least one is continuously engaged and becomes cycle time limiting. In this illustration the campaign consists of three batches.

A characteristic feature of batch production is the need to specify an assignment of units to tasks. In general, this assignment need not be one-to-one; rather, multiple tasks can be assigned to the same unit and multiple units can be assigned to execute the same task. For the recipe of Figure 1, task 4 can be executed in two different units (U1 and U4). Since these two units are inefficiently used in the one-to-one assignment shown in Figure 1a, an improvement in equipment utilisation can be achieved by assigning U1 to execute both the first and fourth tasks, as shown in Figure 1b, thereby releasing U4 for other uses.

3. TYPES OF BATCH PROCESSES

Based on the nature of the product recipes and the allowable task / unit assignments, batch operations can be classified into three basic types.

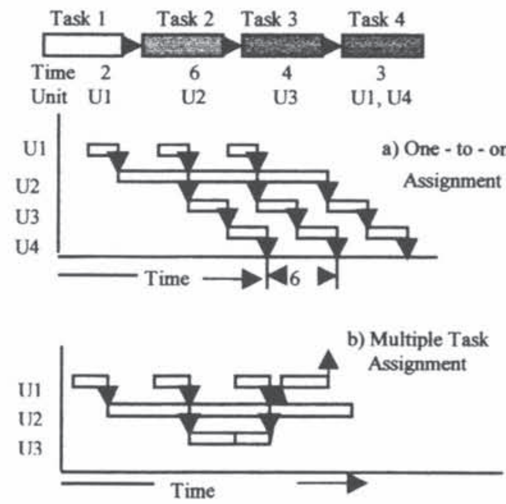

Fig. 1 One-to-one and many to one task to unit assignments

3.1 Multiproduct Plant

Below are the points which characterise the multiproduct plants :

- Employed for a set of products whose recipe structure is the same
- The production line employs fixed many-to-one unit/task assignment
- The line is operated cyclically
- Multiple products are accommodated through serial campaign
- Multiproduct mode is employed for larger volume products (300 to 700 t/y) with similar recipes, such as might be the case with a plant that produces a family of grades of the same product.

A simple representation of this type of plant is given in Figure 2. Normally the products produced in a multiproduct plant are similar chemically and product changeovers are straightforward. The multiproduct plant has been investigated both in the campaign form and in the limiting flowshop form.

In the campaign form, during the given horizon time, various batches of different products are manufactured. For example, in a fixed horizon time (like 1500 hours for a summer season) let's say that

10 batches of A, 15 batches of B and 5 batches of C should be executed to enable to satisfy the demand. There are two ways to realise this procedure;

1. Single product at a time in each campaign: as all the quantity is produced for a specified product, then the other set of cycles begin for the next product (like 10 batches of A then 15 batches of B then 5 batches of C in that campaign).
2. Multiproducts in every campaign : any batch of any product may be followed by a batch of another product before its totality gets completed (like 4 batches of B may get followed by 2 batches of A).

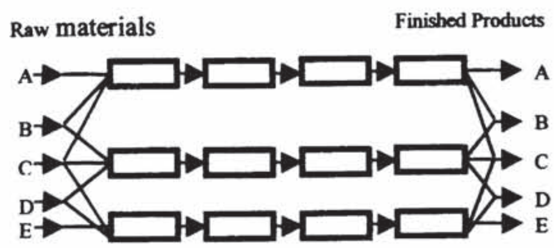

Fig. 2. Multiproduct plant

In the flowshop form, the same recipe structure is used for all products; thus the equipment network is fixed and in addition, batches are scheduled individually rather than in campaigns.

Based on a previously developed LP Flowshop Scheduling Model by Birewar and Grossmann (1990), when maximum profit is taken as the objective function, that can effectively aggregate the number of batches belonging to each product, a Multiperiod LP Model is proposed for the simultaneous production planning and scheduling of multiproduct batch plants that may consist of one or several nonidentical parallel lines. Inventory costs, sequence-dependent clean-up times, and costs, and penalties for production shortfalls are readily accounted for in this model.

The overall planning problem is decomposed into two levels. At the upper level, the planning problem is represented with a Multiperiod LP Planning Model that sets production goals to maximise profit. At the lower level, the scheduling problem is reduced to a sequencing subproblem that must meet the goals set by the planning problem. Penalties are incurred for not satisfying the orders booked. The LP Models also decide which orders are to be satisfied and to what degree in case there is a competition for resources from different orders. The models also determine the amount to be produced for sales in the open market. The LP Models set the production goals for each period and each production line for various products.

Cerda et.al. (1990), proposed a nonlinear mathematical program to search for both the best production strategy and the minimum equipment sizes simultaneously when taking minimum plant capital cost as the objective function. Previously, a MILP formulation helps determine the time efficient multiproduct campaigns to be considered and their associated batch residence times.

It has been shown in the work of Voudouris and Grossmann (1993) that accounting for the effect of final product inventories at the design stage has a significant impact on the profitability of a batch process. The objective is to maximise the net present value. The model considers the allocation of tasks to equipment, location of intermediate storage, sizing of equipment and storage vessels, optimal sequencing of products, and optimal length of the production cycle. The results show that the advantage of the proposed model is that it can systematically account for the many complex trade-offs involved in the problem of synthesis, design, production planning, and scheduling of multiproduct batch plants.

A Branch and Bound algorithm was presented for scheduling N batches or single-product campaigns in the M-unit serial multiproduct batch process with unlimited intermediate storage to minimise the due date penalties in the solution strategy developed by Ku and Karimi (1990). The procedure is feasible for solving problems with N as high as 15. A LP procedure can determine which dominant campaign should be implanted, and the time allocated to them -for maximum profit or minimum time to meet specified product requirements.

3.2 Multipurpose Plant Under Campaign Mode

Multipurpose plants under campaign mode are generally outlined as below:

- appropriate for products with dissimilar recipe structures
- allows many-to-many unit/task assignments
- employs multiple campaigns involving one or more production lines
- each is operated cyclically
- they are prevalent in facilities which produce a large number of products of smaller volume (30 to 300 ton/year).

A simple representation of this type of plant is given in Figure 3. The campaign form of the multipurpose plant is used when product purity requirements are stringent (such as in pharmaceutical production) for reasons of operational simplicity, or to facilitate batch consistency.

In the studies of Wellons and Reklaitis (1989) (which takes maximum processing rate as the objective function), optimal schedule generation for a single and a multi-product production line is examined. Based upon the observation that equipment group sequencing and path batch-size determination are important aspects of the production line scheduling problem, a MINLP formulation for this problem is presented which incorporates these decisions. In 1991, the formation of single and multiple-product campaign formation and production planning is addressed.

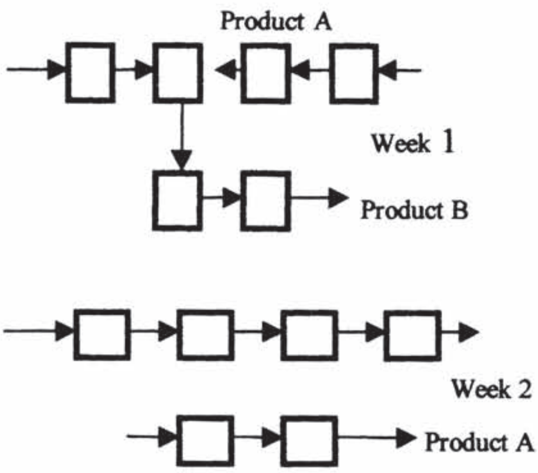

Fig. 3. Multipurpose batch plant under campaign mode.

A general mathematical formulation for multiple campaign planning/scheduling of multipurpose batch/semicontinuous plants is presented in the study of Papageorgiou and Pantelides (1996). The problem involves the simultaneous determination of the campaigns (ie., duration and constituent products), and for every campaign the unit-task allocations, the task timings, and the flow of material through the plant. The problem is formulated as a single-level mixed integer linear programming model.

3.3 General Multipurpose Plant

It is a multipurpose plant operated with no defined production lines; rather production occurs in an aperiodic fashion involving many-to-many unit/task assignments on an individual batch basis. The general form allows more effective use of capital equipment at the cost of operating complexity and additional change-over-costs. If production requirements of individual products are small and cross-contamination risks low, then it is advantageous to relax the structures of the campaign production mode and to allow product tasks to be executed in an acyclic fashion as needed to meet specific order deadlines. A simple representation of this type of plant is given in Figure 4.

4. REMARKS

Depending on the business environment as well as on the availability of accurate information concerning future demands for all potential products being produced, batch / semicontinuous plants usually operate in one of two distinct modes. In the absence of reliable, long-term information, plants tend to be operated in a short-term mode, with the production plan being largely determined by the currently outstanding orders. This usually implies relatively short planning horizons (typically ranging from one to a few weeks). The pattern of operations in any schedule is usually irregular with production being different from one planning interval to the next due to the varying nature of outstanding orders. If on the other hand, reliable long-term demand predictions are available, it is often preferable to partition the planning horizon into a number of relatively long periods of time ("campaigns"), each dedicated to the production of a single product or a subset of products. This campaign mode operation may result in important benefits such as minimising the number and costs of changeovers when switching the production from one product to another. The complexity of management and control of the plant operation is further reduced by operating the plant in a more regular fashion, such as in a cyclic mode within each campaign, with the same pattern of operations being repeated at a constant frequency. Typical campaign lengths are from a few weeks to several months, with cycle times ranging from a few hours to a few days. The campaign mode of operation is often used for the manufacture of "generic" materials (e.g., base pharmaceutical) which are produced in relatively large amounts and are then used as feedstock or downstream processes producing various more specialised final products. Each of these problems itself constitutes an exciting area for research and development of a computational nature.

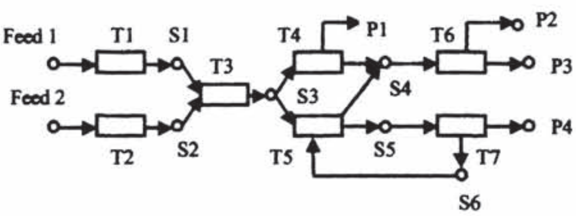

Fig. 4. General multipurpose plant

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