# Production control in multipurpose batch process industries : a research proposal

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# Production Control in Multipurpose Batch Process Industries: A Research Proposal

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# Production Control in Multipurpose Batch Process Industries: A Research Proposal

## 1. Introduction

Only in the last decade a considerable research effort aimed at the design and scheduling problems in batch process industries can be observed. For quite a long time, research in chemical engineering process design has been aimed at the development of continuous processes (Rippin 1983a, Reklaitis 1990). Initially new products tended to be produced in batch processes, but the engineering objective was to develop a continuous way of production as early as possible . Continuous processes have several distinct advantages over batch processes, of which better process control is the most appealing one. However, still a large portion of the world's chemical production is produced in batches. This is largely due to two reasons. The first one is that some products simply cannot be processed continuously on technological grounds. The second reason, which is valid for many more products, is that a lot of products are produced in batches on economical grounds. Batch production is usually performed in more or less standard equipment which can easily be reconfigured to produce different products (Rippin 1983a). This reflects the increasing market for low volume products (specialties), as opposed to the typical high volume products in the market for continous processes (bulk). Quite contrary to continuous processes, batch processes are characterized by not only design, but also by scheduling problems.

Batch process industries have received limited attention in the traditional production planning and scheduling literature in operations research (OR), management science (MS) and production and operations management (P/OM) (Fransoo and Rutten 1993). However, in the last decade, the chemical engineering literature has demonstrated an increased interest in the design, planning and scheduling problems in batch process industries. This paper intends to give an overview of this research from an operations management / production control point of view, in order to be able to define research needs in this area. This paper is therefore not primarily intended to give an overview regarding the technical details of the approaches used. For these issues, we refer to the surveys by Rippin (1983b) and Reklaitis (1990).

## 2. Definition

A batch process industries planning & scheduling problem is characterized by the following attributes (adapted from Yeh and Reklaitis (1987) and Wellons and Reklaitis (1989)).

1. A set of products, the production requirements for each product, its selling price, and the available production horizon.
2. A set of feasible equipment items classified into equipment types. These are various kinds of manufacturing equipment possibly differing in the kind of processes they are able to perform, in size, or in other characteristics. The characteristics of each equipment item should be known.
3. Recipe information for each product consisting of the sequence of chemical and physical steps which must be performed, the nature of these steps (batch or semi-continuous), the size/duty factors (usually the volume which must be produced in the step per unit mass of final product) and the processing time/rate relationships associated with each step. The difference between batch and semi-continuous production steps lies in the timing of the input requirements and the availability of output. In the case of batch steps, the input materials are required at a distinct moment in time

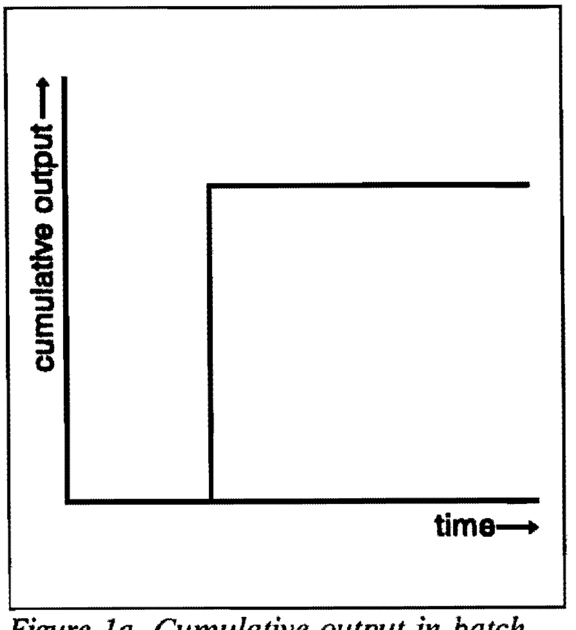


*Figure 1a. Cumulative output in batch processes*

and stay for a period of time in the processing equipment before becoming available as a batch at a distinct moment in time (see Figure 1a).

In the case of semi-continuous steps, there is a continuous flow of input materials going into the processing equipment and leaving the processing equipment, with a delay in time between the two (see Figure 1b). In general, the time between the input and output in semi-continuous processing is considerably shorter than in batch processing.

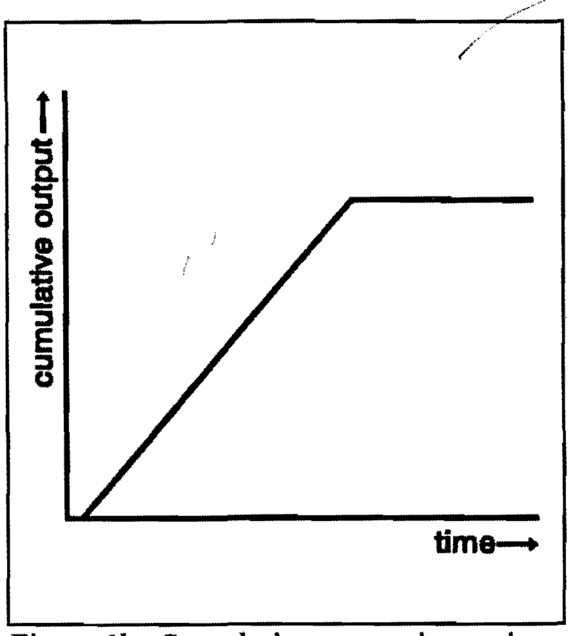

*Figure 1b. Cumulative output in semi-continuous processes.*

The nature of the process also determines whether a processing time can be specified (in batch steps) or a processing rate (in semi-continuous steps). The processing time is generally not a constant, but is related to the yield function of the batch process. An example of such a function is represented in Figure 2 (based on Rippin 1983a). In this figure, the vertical axis represents some performance measure of the output of the batch process, while the horizontal axis represents the processing time. During the first part, there is no output at all. During this time, changeover may take place, as well as cleaning activities. Additionally, some minimum time may be required before any output is generated. The performance curve itself is represented as a monotonic and nondecreasing curve, since if the performance would deteriorate at a certain moment in

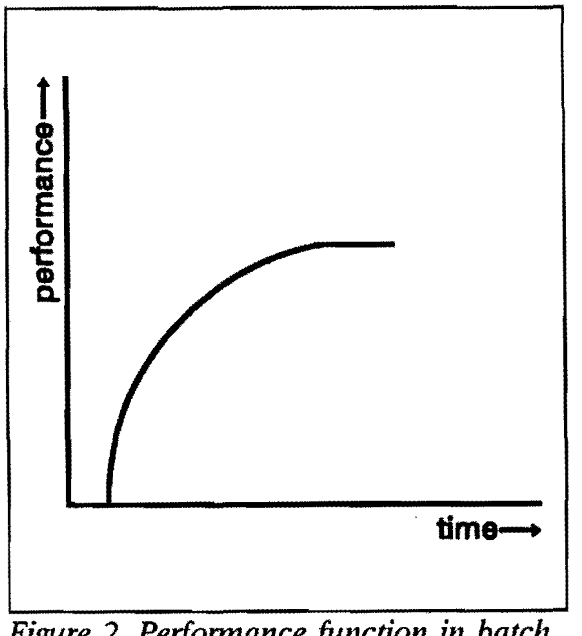

*Figure 2. Performance function in batch processes.*

time, the process could always be stopped at that moment.

The degree of similarity between the products determines whether the problem refers to a multiproduct plant or a multipurpose plant (Rippin 1991). In multiproduct plants, production lines are not shared among different products during a single campaign. In multipurpose plants they are, since less similarity exists between the various product recipes and routings.

4. The status (stable or unstable) and the transfer rules for the intermediates resulting from each recipe step. The consequence of an unstable status is that a batch which is completed needs to be processed immediately at the next processing step and cannot be put in intermediate storage or held in the reactor ("zero-wait").
5. The set of equipment types which are feasible and appropriate for each recipe step.
6. Resource utilization requirements or rates associated with each step of the recipe. This refers to resources such as heat and power. In general the requirements may be different for each feasible step-equipment type combination.
7. The lost production time and costs associated with change-over between products.
8. Inventory charges for each product and intermediate per unit of time. Inventory restrictions (e.g. maximum vessel capacity).
9. A suitable performance function involving capital and/or operating costs and sales revenue.

## 3. Planning and Scheduling

In the literature in this area, the terms *planning* and *scheduling* have not been used consistently throughout the research community. In general, however, planning is associated with a longer term horizon and, therefore, involves less detail. The exact line between planning and scheduling problems depends upon the way in which the general problem is decomposed. In this respect, *decomposition* is referred to as the methodology which splits a complex problem into two or more subproblems, which can be solved either independently (by introducing some coordination function) or sequentially (by which the result of one subproblem is (part of) the input for (the) other subproblem(s). (Bertrand *et al.* 1990, Giesberts 1993).

Sequential decomposition in a hierarchical scheme for operations planning and scheduling in batch chemical plants is proposed by Jänicke (Jänicke 1983, Biess and Jänicke 1986, Jänicke *et al.* 1991). In this method, the planning function transforms (external) customer orders and/or inventory positions into (internal) production orders using lotsizing rules. The internal production orders are then characterized by the product specifications, the number of batches, due dates and priorities. These production orders (or *jobs*) are then processed in some scheduling algorithm or heuristic to obtain a production schedule. This includes the allocation of product synthesis steps (necessary to complete a production order) to equipment units and to specific time slots. Jänicke *et al.* (1991) further split this latter scheduling problem into two (sequential) scheduling subproblems of which the first one involves the detailed scheduling of campaigns, while the second one involves the detailed scheduling of batches. Campaign scheduling roughly schedules the bottleneck resources and determines the exact number of batches, while detailed scheduling involves the allocation of all synthesis steps to the manufacturing equipment.

With regard to decomposition, it should be noted that in some publications planning/scheduling problems are defined as subproblems in the design of batch chemical plants. Specifically, in these cases some kind of "standard" schedule is created on which the determination of equipment sizes is based. A contribution to this area is the work by Birewar and Grossmann (1989). They show that a more detailed study of the scheduling problem within the plant design phase may be extremely beneficial in terms of capacity investment. Their approach leads to some kind of campaign schedule.

A similar approach is presented by Mauderli and Rippin (1979). In a clear article they outline their procedure which essentially enumerates a large number of possible campaigns. A screening and selection heuristic then selects the dominant campaigns which together make the production plan.

A major difference between the approach presented by Jänicke and the approaches in the design context is the demand characterization. In the former case, it is assumed that a number of actual external orders exist and/or are generated by the inventory management function. In the latter instance, actual external orders are not yet present, since this involves part of a design problem. Therefore average *expected* demand levels are used. It should be noted that in both cases demand is dealt with as if it were deterministic.

In case of demand which is stable and known well in advance, the latterly proposed planning procedures may be extended to complete schedule generation. Because of the environmental stability, and limited size of the problem, a distinction between planning and scheduling may not have to be made. To this purpose, Mauderli and Rippin (1980) have extended their enumeration and selection procedure to a scheduling program (Batchman). The procedure starts by enumerating all possible sets of equipment which can be used to manufacture a certain product. These sets are called batches. All batches are evaluated regarding their likelihood to be incorporated into an optimal schedule. Batches with an expected bad performance are eliminated. Next, production lines are enumerated. A production line is defined as a sequence of consecutive batches. A production line may consist of a single batch being repeated or of multiple batches. Again, all generated production lines are evaluated and an elimination procedure is started. Finally, campaigns are generated. A campaign is defined as a set of production lines producing the same or different products. During a campaign, equipment cannot be shared between production lines. This limits the application of this procedure to multiproduct plants and thus excludes multipurpose plants. Dominant campaigns are selected based on their average performance. Finally, a schedule is constructed using a mathematical programming technique which selects the campaigns to be set up and the time allocated to each campaign.

A procedure with a similar structure (enumeration, elimination, optimization) for multipurpose plants has been presented by Lazaro *et al.* (1989). Obviously, this procedure requires more advanced techniques in the various steps of the procedure, since multipurpose plants are more complex than multiproduct plants.

We may conclude that it is necessary to properly define the distinction between planning and scheduling in batch chemical industries. The necessity to distinguish the two and the methodology to separate the two depends heavily upon the complexity characteristics of the batch plant considered. In the next section we will discuss some issues regarding these complexity characteristics.

## 4. Degree of Complexity.

The first set of characteristics (which are summarized under 1 in the introductory section) roughly determine the approach towards the production planning and control problem. First of all, the number of products is important. If the number of products is limited (e.g., less than 10), more or less cyclic schedules can be determined. Determining these schedules is usually done for quite a long horizon, i.e., the production schedule is fixed for a number of months ahead. In these situations, the production planning function determines the maximum output of the plant and the standard number of batches which are produced consecutively. The production scheduling function schedules the detailed batches of every product on each installation. Most companies use some kind of Gantt-chart (either operated manually or by a computer program). The literature reports also on the use of mathematical algorithms in the Gantt-chart interfaces (Cott and Macchietto 1989b, Mauderli and Rippin 1980, Lazaro *et al.* 1989, Jänicke 1992; for a review see also Ku *et al.* 1987).

If the number of products is high, the available algorithms in the literature do not seem applicable. In some plants, the number of products would be a few hundred. Theoretically, a model may be constructed which describes all products, synthesis steps and production facilities. However, the mere size of the problem would make it unsolvable and decomposition of the problem is required. The literature does not report on problems of this degree of complexity (Biegler *et al.* 1988).

The second denominator of the problem complexity and its consecutive approach is the uncertainty in the production requirements and the manufacturing process. The scheduling approaches presented in the chemical engineering literature mainly address deterministic demand problems, although in some papers developments towards more stochastic problems can be noticed. Rudimentarily two different approaches to capture uncertainty can be found in the literature. In this paper these two are identified as *on-line scheduling* and *simulation*. In on-line scheduling (Cott and Macchietto 1989a, Cott and Macchietto 1989b), fast rescheduling algorithms are developed that are able to quickly generate a revised schedule when a change in the processing time of a batch occurs. Their proposed procedure (Cott and Macchietto 1989a) basically creates a revised schedule by shifting batches forward and backward depending upon the actual completion times of the batches compared to the scheduled completion times. The performance of their heuristic is evaluated by the resulting average batch time and average cycle time. An evaluation of makespan is not provided.

In the simulation approach, schedules are evaluated and adapted based on a simulation of the actual manufacturing process. Modeling the manufacturing process such that it is suitable for simulation however requires substantial knowledge of the manufacturing process, such as distribution function of the batch process times. A clear review is provided by Biegler *et al.* (1988), relying on the features of the BOSS package by Joglekar and Reklaitis (1984).

The limited attention for uncertainty in the scheduling approaches presented in the literature may be justified from a production control point of view. It remains a point of discussion whether this uncertainty be captured at the production scheduling level or the production planning level. It is very well conceivable that the uncertainty be captured at the production planning level by introducing either safety stocks or demand management procedures which may considerably reduce the uncertainty at the operational scheduling level. This leaves however a need for research at the production planning level. The exact formulation of the uncertainty characteristics and flexibility requirements is acoording to Rippin (1993) still in the problem definition stage of research.

Thirdly, the required customer delivery time influences the various opportunities to solve a scheduling problem. First, there is the ratio between the required customer delivery time and the production lead time. It is apparent that this production lead time is influenced by the capacity utilization in the plant. If the capacity utilization is low,

schedules with little waiting time in between the various synthesis steps can be generated more easily than if capacity utilization is high. The solution procedures suggested in the literature generally assume that sufficient capacity is available so that the lead time is not influenced more than necessarily by waiting time. However, if capacity structures become complex (not a single bottleneck) and the number of products is high, it may not be straightforward -- if not impossible -- to determine a schedule which is essentially based on a zero-wait or no-intermediate-storage policy.
If the required delivery time is longer than the current production lead time (independent of the control structure), production can be order-based and each customer order may be translated into a production order which may then be scheduled. Problems may rise in this case if the minimum required size of a production order exceeds the typical customer order size. Combination of customer orders may then be necessary, depending upon which inventory holding may be neccessary.

If the required delivery time is shorter than the production lead time, production to stock is necessary. Production may be completely to stock (all final products are kept in inventory) or intermediates may be kept in stock. This is especially advantageous if the number of intermediates is limited and the number of end products is considerably larger. Divergent product structures invite to such an approach, which is known in discrete production systems as "assemble-to-order", but has not been addressed in a batch process industries environment.

## 5. Retrofitting

Retrofitting is the physical redesign (including capacity expansion) of existing installtions in multipurpose batch plants. The major problems in this area having been investigated and published in academic journals refer to the (usually cost-)optimal solutions of capacity expansion problems given changes in requirements and the current plant configuration (e.g, Espuña and Puigjaner (1989), Gunderssen (1990), Papageorgaki and Reklaitis (1993), Reklaitis (1990), and Vaselenak *et al.* (1987)). In multipurpose plants, physical reconfiguration may be necessary in between two campaigns. If the sets of products of the two consecutive campaigns are characterized by very different synthesis steps, considerable retrofitting activities may be necessary. It is at this point that planning and design problems interact most closely.

## 6. Planning and Scheduling in Real Business.

The characteristics mentioned above describe the theoretical problem as it has been recognized in the literature and extended by our analysis. However, in practice many constraints are present which limit the application of straightforward solution methods and heuristics of problems formulated in the above terms. These additional constraints may be found in a number of areas.

First, let us consider the demand management aspect of the production planning and control problem. Demand management is a complicated function which does not only involve the balancing of capacity and material demand and availability, but also addresses the distribution of the available resources over the customers. This is related to the market situation of the company, whether general capacity is sufficient to fill demand or whether considerable imbalances exist between the required and the available resources. This influences the management function differently.

Second, the physical resources available on the production floor should be considered. First, this refers to the available capacity units. Roughly, it can usually be determined which synthesis steps or other chemical or physical steps can be performed on a specific unit. However, additional constraints may be less easy to implement into a formal description of the problem (in mathematical terms or similarly exact). In this respect one could think of different output/performance functions at specific reactor vessels, limited transportation facilities between certain pairs of vessels, different (brands of) devices connected to a vessel, etc. Next to the capacity units (reaction vessels), this may also involve the presence of intermediate storage facilities.

## 7. Problem Definition

The problem to be studied can be described by the following general question:

*How should production planning and control be performed in multi-purpose batch process industries with considerable retrofits in between campaigns and/or considerable change-overs between production batches?*

Special attention is given to:

* the representation (model building), at the (aggregate) planning decision level, of the detailed scheduling problem and decision procedure.
* the decomposition of the detailed scheduling decision.
* the practical considerations for implementing such a procedure
* the use of existing scheduling algorithms, especially the ones used in the chemical engineering community and the MS/OR algorithms for flow shops.

For the development of a concept as proposed above, an engineering approach will be chosen which is aimed at the gradual design of a control model. The first step would be to describe a single production situation and the relevant present scheduling techniques. Consecutively, the scheduling methodology would have to be decomposed from an operations management point of view and an hierarchically structured procedure be developed. this model should be tested both theoretically and in practice.

## 8. Conclusion

This report has presented an overview of the literature in the area of planning and scheduling in batch process industries. It identified a gap between the complexity in many business applications and the restrictions on the use of many scheduling algorithms and heuristics.

However, many algorithms and heuristics have considerable value to limited versions of the problem studied and could be helpful in defining more general control structures.

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