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Production Control in Batch Process Industries: A Literature Overview

1. Introduction

Production control research has always been focused on the manufacturing of discrete products. Little attention has been paid to process industries. However, process industries take account of a big part of the total industry. That process industries differ from discrete manufacturing is shown in the next section. As a result, production control in process industries needs special treatment.

Production control is defined as the coordination of supply and production activities in manufacturing systems to achieve a specific delivery flexibility and delivery reliability at minimum cost [Bertrand, Wortmann & Wijngaard, 1990]. A production control concept is a description of and relations between all decision functions regarding the management of materials flow and capacity resources. Because strategical, tactical and operational decisions are normally taken on different levels in the organization a hierarchical approach to the production control problem is used. An advantage of hierarchical control is that the decomposition leads to less complex subproblems that have to be solved. The decisions taken at a higher level form constraints for the lower levels.

On the strategical level decisions are taken on the markets to operate upon, the type of products to produce (not the individual products) and the design of the production facility. On the tactical and operational level decisions regarding the allocation of production capacity to products takes place. Some companies develop medium term sales and production plans, others only plan on a very detailed level often by using scheduling algorithms.

The aim of this paper is to give an overview of the literature available on the different decision functions regarding the management of materials flow and capacity resources in batch process industries. First a description is given of the characteristics of process industries and a distinction is made between different types of process industries. Then the design problem of batch process industries is discussed and some important methods are described. In the fourth section the allocation of capacity to products is discussed.

2. Batch process industries in perspective

2.1 Characteristics of process industries

Process industries are defined as businesses that add value to materials by mixing, separating, forming or chemical reactions. Processes may be either continuous or batch and generally require rigid process control and high capital investment [Wallace, 1984].

For a long time production control research has focused on the manufacturing of discrete products. Process industries have some typical characteristics that make them different from discrete manufacturing. The most important characteristics are [Kochalka, 1978][Fransoo & Rutten, 1994]:
- Variable yield
- Natural variations in quality of raw materials (potency)
- Variations in bills of material (recipes)

- Divergent flow; many finished products from a few raw materials
- By-products
- Unit of measure differences for production and product
- Number of packaging (bulk, tank, jar)
- Rigid technical constraints (standard reaction batch, storage possibilities, couplings)

Although these characteristics can be found to some extent in discrete manufacturing as well, they are of great importance to process industries. The above mentioned characteristics are typical of process industries, however, they are not found in every business in the process industry.

2.2 Batch processes versus flow processes

As a matter of fact there exists a large variety of businesses within the process industry. APICS makes a distinction between batch/mix and process/flow. Batch/mix is used for a process business which primarily schedules short production runs of products. Process/flow stands for a manufacturer who produces with minimal interruptions in any one production run or between production runs of products which exhibit process characteristics such as liquids, fibers, powders, gases [Connor, 1986].

From the APICS point of view a process business is characterized as batch or flow according to the interruptions in the production. If production runs are short and, as a result, there are relatively many changeovers, a process business is called a batch business. This definition reflects the entire production process. On the level of individual processing steps a distinction between batch and continuous processing can be made. If a processing step starts and ends at a discrete point in time it is called batch. In this case the equipment units are vessels of some kind, which undergo cycles of filling, processing and emptying. When a process step is carried out continuously, there is a continuous input and output of materials and (intermediate) products. In this paper the APICS definition is followed because in many cases a combination of batch and continuous processing steps is found.

Fransoo and Rutten [1994] present a one-dimensional typology for process industries with process/flow on one extreme and batch/mix on the other. This typology is presented in figure 1. This typology shows that from batch/mix to process/flow you find a large variety of process businesses. The characteristics of process/flow and batch/mix businesses given by *Fransoo and Rutten* are summarized in table 1.
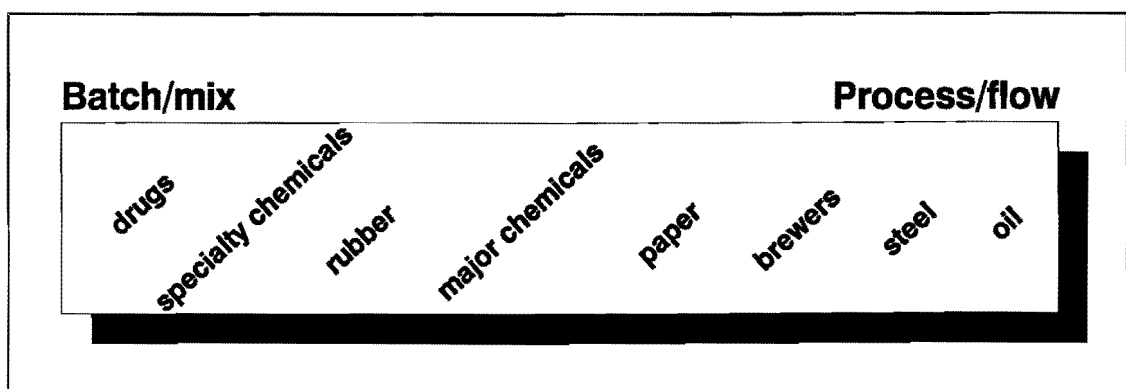

Figure 1: One dimensional typology for process industries (Fransoo & Rutten, 1994)

Puttman [1991] uses a two-dimensional characterization. Within a manufacturing process he defines logistic units, that are the smallest identifiable subsystems in the production system in which a specified product change takes place and for which the subsequent output stream, with regard to the moment and/or location of arrival, can be varied. For these logistic units an intraunit and interunit description is given:

- an intraunit description of the manufacturing process: the result is basically a discrimination between process industries and non-process industries
- an interunit description of the manufacturing process: the result is basically a discrimination between job shop and flow shop.

The combination of the two dimensions results in four types of businesses. The strong point of this typology is that it shows both the variety within the process industry and the possible similarity between process industries and non-process (discrete) industries. This prevents that process businesses are seen on one extreme and discrete businesses on the other.

Table 1: Characteristics of process/flow versus batch/mix businesses (Fransoo & Rutten, 1994)

Process/flow businesses are characterized by	Batch/mix businesses are characterized by
• High production speed, short throughput time	• Long lead time, much work in process
• Clear determination of capacity, one routing for all products, no volume flexibility	• Capacity is not well-defined (different configurations, complex routings)
• Low product complexity	• More complex products
• Low added value	• High added value
• Strong impact of changeover times	• Less impact of changeover times
• Small number of production steps	• Large number of production/process steps
• Limited number of products	• Large number of products

As can be seen from the characterization of *Fransoo & Rutten*, batch process industries are generally found in cases of low volume products of high added value. Because a large number of different products is made, is batch production usually carried out in relatively standardized types of equipment. These equipment units can easily be adapted, and if necessary reconfigured to produce many different products. The flexibility of the production arrangements can also cope with the fluctuations or rapid changes in demand which are often characteristic of products of this type [Rippin, 1983]. Batch process industries need to be very flexible both in product mix as in product volume. This flexibility not only concerns the existing set of products, but also with the capability to produce new products.

2.3 Multiproduct and multipurpose batch plants

Basically there a two types of batch process industries: multiproduct and multipurpose. In the multiproduct situation a set of different products is produced all following the same routing. In multipurpose batch plants different products do not follow the same routing. It is even possible that two succeeding batches of the same product follow different routings. Products that do not use the same equipment units can be produced at the same time. In a multipurpose plant the equipment units have to be configured into a production line for each product or family of products. At one time more then one nonoverlapping production lines can be in use. It will be clear that multipurpose plants provide more flexibility than multiproduct plants.

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3. Design of the production system

3.1 The design problem

In the grassroots design case the problem of designing an entirely new plant is considered. *Rippin* [1993] names three necessary components for producing chemical products:

1. a market for one or more products
2. a sequence of processing steps, whereby raw materials are converted into products
3. a set of equipment in which the process tasks are carried out.

First a market for one or more products has to be determined. Batch process industries often produce low volume, high added value products. These products in general have short product life times and the demand uncertainty is high. As a result one commonly has to deal with multiple and poorly defined product requirements in the design phase. Therefore sufficient flexibility should be provided in the design of the plant.

The second component is the sequence of processing steps for the different products. These are for a great deal the result of product development. The possibilities of merging sequential steps into one step or splitting one step into more steps depends largely on technical constraints. The introduction of intermediate storage needs attention at this point. Intermediate storage will only be possible when the state of the intermediate product is stable.

According to the similarity of the succeeding processing steps for the several products produced in a batch plant a choice for either a multiproduct or a multipurpose plant is made. If production volumes justify the existence of more than one production lines the decision on the number of lines and the allocation of product (families) to one or more lines should be made in the design phase.

The third component mentioned by *Rippin* is the set of equipment needed. From an efficiency point of view one tries to solve incompatibilities between equipment units. These incompatibilities can reflect to cycle time or batch size. The cycle time is defined as the time between two consecutive batches of one product. When we assume that each processing step is carried out by one equipment unit the cycle time is determined by the processing step with the longest processing time. The batch size, often expressed in kilograms of the final product, is determined by the processing step which can produce the smallest amount. Incompatibilities lead to underutilization of equipment units with larger batch sizes and/or shorter processing times.

Cycle times can be decreased by putting an equipment unit in parallel and out-of-phase. This means that consecutive batches can be processed on one of the parallel units. Batch sizes can be increased by putting equipment units in parallel in-phase. In this case the batch is split, processed at the same time on the parallel units and recombined afterwards. Another possibility is to split the longer task into succeeding smaller tasks. In the same way several small tasks can be merged to achieve cycle times of approximately the same length [Reklaitis, 1990] [Rippin, 1991].

The insertion of intermediate storage between two consecutive tasks allows for different batch sizes and cycle times up- and downstream of the storage point. *Reklaitis* [1990] gives three advantages of partitioning of the processing network into independent subnetworks by intermediate storage. First, if several products need the same intermediate product partitioning offers the possibility of sharing the same processing equipment. Second, it may allow equipment cost savings through the additional degree of freedom provided by the

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selection of independent processing rates or capacities for the subnetworks. Third the reduced recipe structure for the final product may allow faster response to product demands.

In batch plants only on a highly exception one single product is made. Normally a large variety of products is made, either in a multiproduct or multipurpose way. These different products often do not have the same processing time requirements. Furthermore the batch size requirements can differ for the products, due to differences in the equipment size (volume) needed to process a certain amount of product (kilograms). Solving incompatibilities becomes more difficult when processing times differ from one product to another. This especially holds for multipurpose plants in which a great variety of products is produced, and the routings are not the same for the products.

When more than one equipment unit of a certain type is required the designer has to choose whether the sizes should be the same for all units. In cases where different batch sizes are required over time it can be desirable to have a group of equipment units not all having the same size. *Reklaitis* [1990] advocates though that in the grass roots case it is preferable to design for simple operations by only allowing identical parallel groups of equipment to be used for any task. If different batch sizes are used and processing times are dependent scheduling becomes very complicated.

The solution methods discussed in 3.2 and 3.3 deal with finding a set of feasible equipment units with which a certain production plan can be realized against minimal capital cost. The batch sizes of the equipment units and the number of equipment units used in parallel are chosen in such a way that incompatibilities in batch sizes and cycle times are low. In 3.2 the design of multiproduct batch plant is considered. In 3.3 the design of multipurpose batch plants is discussed.

3.2 Solution methods to the design problem of multiproduct batch plants
In this section some solution methods available in the literature are discussed. Those papers are mentioned that are referred to in many other papers and that together provide a good overview of the available methods. As such, both heuristic and deterministic methods are given.

Biegler, Grossmann & Reklaitis [1988] consider the design of processes in which batch and continuous operations are combined to produce multiple products. The multiproduct batch plant consists of a set of products, a network of equipment units, a set of rules for the transfer of products from one processing step to another, for each product a recipe consisting of a set of processing times and resource utilization levels. In addition change-over times can be specified. There are three possible transfer rules considered; zero wait, no intermediate storage and finite intermediate storage. The design problem for multiproduct plants is solved with non linear programming (NLP) under the assumptions of all stages of processing operating in the zero wait mode, which means that succeeding processing steps have to follow each other immediately. Furthermore the assumption is made that production occurs in long single-product campaigns. In this case only the time utilization of the equipment units is considered, and the processing yields and materials utilization are independent of equipment size or processing rate. The capital cost of equipment is used as an objective function assuming that equipment costs are given by power law correlation to the size or capacity of the equipment units. Both batch and continuous equipment constraints are taken into account. For the cycle time constraints explicitly attention is paid to filling, processing and emptying of batch stages that are coupled to continuous stages. This is necessary because the system operates in the zero wait mode. Furthermore a production time constraint is formulated that makes sure that the required amount of products is produced in a certain time period. The formulated optimization problem is solved using nonlinear programming methods. Structural

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choices concerning intermediate storage and merging or splitting of tasks are not included in this formulation.

Sparrow, Forder & Rippin [1975] consider the sizing of batch equipment for a multiproduct plant. First a heuristic method is discussed that consists of three parts: 1) calculation of the exact equipment sizes given the number of equipment units in parallel (out of phase); 2) conversion of exact sizes in to standard sizes; and 3) choice of the number of equipment units in parallel. By a weighting procedure the characteristics of the actual products are converted to a new hypothetical product. Both batch size requirements and production time requirements are taken into account. The conversion to standard sizes is carried out by first rounding up the sizes to their next larger standard size and then evaluating the effects of using one standard size smaller. If the production time requirements are not violated the smaller size is used. The last step is determining the number of units in parallel. Initially this number is set to one for all stages. By increasing this number by one at a time for each stage and adapting the batch size the effect on capital cost is evaluated.

A second method considered by *Sparrow, Forder & Rippin* [1975] is a branch and bound method. First an upper limit is set upon the number of equipment units in parallel for each stage. It is assumed that equipment is available only in standard sizes and that equipment units used in parallel have identical sizes. Together this results in a finite number of states for each stage. The set of possible solutions may be viewed as a tree. With this branch and bound method an optimal solution based on minimizing equipment cost is computed.

Both methods were programmed and compared using randomly generated problems. For many of these problems both methods gave the same solution, the heuristic method requiring considerably less computing time. Solutions found with the heuristic method were on average within a few percent of the optimal solution.

Espuña, Lazaro, Martinez & Puigjaner [1989] propose an optimization strategy for the design op multiproduct plants based on gradient calculations, which reduces the computing time when compared with the available heuristic procedures and deterministic nonlinear programming techniques. Like in other methods the goal is to optimize the sizing of the manufacturing process units by minimizing a cost function, subjected to specific plant operating conditions. Both batch and semicontinuous equipment is taken into account. Only single product campaigns are considered. Both sizing of and restrictions on utilities are not taken into account. There is no delay between consecutive jobs. Each unit is utilized no more than once per batch. Parallel equipment both in and out of phase are allowed. Equipment sizing is not restricted to a set of specific values, but only to a predetermined range. All equipment items parallel are identical.

The basic restriction chosen by *Espuña, Lazaro, Martinez & Puigjaner* is the Surplus Time (SP), which is the difference between the available time and the total production time. The optimal sizing will be then obtained by minimizing the objective function while keeping the surplus time positive. If the surplus time becomes negative the production plan for the set of products cannot be met. For a given number of parallel units and an initial sizing a solution is found in an iterative way. If the current sizing corresponds to a feasible solution (SP>0), the unit which most improves the objective function without excessive loss of marginal time will be selected to be modified. In case of an infeasible solution the selected unit is the one that gives the highest increase in marginal time at the lowest penalty cost. The equipment size will be reduced or enlarged for the feasible and non-feasible case respectively. The amount by which the equipment is reduced or enlarged is given by the step-size (*h*) for that equipment unit. That is the factor between 0 and 1 to multiply or divide the current size to obtain the next size of selected equipment. When passing from a feasible solution to a non-

feasible the step-size is changed to $(h+1)/2$. When a bound in the size of equipment units is reached, the step-size of the selected equipment unit is reduced in a greater amount. The optimization procedure ends when all step-sizes become insignificant (close to 1). The same procedure can be repeated for other numbers of parallel units.

Several cases mentioned in literature were tested by *Espuña, Lazaro, Martinez & Puigjaner*. The results show a large reduction in computing time with no significant difference in the objective function.

The assumptions that production occurs in single-product campaigns is often found in methods for the design of multiproduct batch plants. In all papers mentioned earlier in this section the incompatibilities in the configuration are solved assuming single-product campaigns. Anticipating the impact of scheduling at the design stage can result in significant savings in the capital cost of multiproduct batch plants [Birewar & Grossmann, 1989]. Because different products have different time requirements for the equipment units the use of mixed product campaigns can be more efficient. For example product A has a large time requirement for the first processing step and a small requirement for the second. For product B it is the other way around. In this case it can be efficient to produce A and B together in a mixed campaign instead of in two single-product campaigns. Idle times can be reduced to increase the utilization of equipment. Another advantage is a more steady supply of product. Whether the use of mixed product campaigns is more efficient than single product campaigns is largely dependent on the time needed for clean-up between two products.

As we stated earlier flexibility is of extreme importance to the batch process industries. The solution methods discussed so far, do not take into account flexibility. *Wellons & Reklaitis* [1989a] concentrate on the design of multiproduct batch plants under uncertainty. A distinction is made between short-term variations and long-term variations. Short-term uncertainties include processing time and recipe uncertainties of the individual products. These can be accommodated by overdesign or the manipulation of operating variables or by intermediate storage. Long-term variations arise in the available production time and the required production quantities of individual products. Seasonal changes in demand pattern can be accommodated by employing higher levels of production or an increase in product inventory. Long-term demand uncertainty is best accommodated by plant expansion.

Several solution approaches to the design problem under uncertainty are described. In the worst case approach the solution procedure is identical to the deterministic problem with the difference that the uncertain parameters are set to their upper or lower bound values. The wait-and-see approach requires a separate design for each realization of the uncertain parameters. For each subproblem a solution to the complete design problem has to be obtained. To decrease computational time the constraints are divided into hard and soft categories. The hard constraints must always be satisfied will the plant operate. The soft constraints represent the capability to meet the given production requirements. In the probabilistic approach the constraints containing the uncertain parameters are relaxed so that rather than requiring these constraints to be always satisfied the probability of constraint satisfaction can be specified by the designer. In the two-stage formulation the equipment sizes are determined at the design stage and the effects of the uncertainty parameters on systems performance is established in the operating stage.

Wellons & Reklaitis propose a solution method in which the uncertainties are divided into long- and short-term categories and appropriate policies for accommodating both groups of uncertainties are required. The constraints are separated into hard and soft categories. For the hard constraints the uncertain parameters are set to the upper bound to ensure feasibility of these constraints. As opposed to the methods discussed earlier the objective function does not

only represent the cost of the equipment, but also includes a measure of expected system performance. A penalty function may be used to take into account the expected revenue loss due to unfilled orders. If long-term variations are accommodated by plant expansion a multistage formulation of the objective function is required. The mixed integer non linear programming (MINLP) formulation used only allows expansion by adding identical batch units which operate out-of-phase. For each expansion, a two-stage problem must be solved to evaluate the flexibility of the new design.

3.3 Solution methods to the design of multipurpose batch plants

Biegler, Grossmann & Reklaitis [1988] also consider the design of multipurpose plant. The following elements are considered: a set of products, a collection of equipment units, for each task a set of admissible unit types, a set of transfer rules and for each product a recipe. Compared to the multiproduct case some additional assumptions are made: only nonoverlapping production lines can be used at the same time, each product has a unique configuration, if an equipment item is used in a configuration all units of that type are used, all equipment is available over the same total production time. Products that do not need the same equipment are grouped. Each product is placed in exactly one group. The production time constraint differs from the multiproduct case in the way that for each equipment unit account is taken only of the production time required by each of the products that require that stage. In the multiproduct plant each product needs every equipment unit. In the multipurpose plant a product needs only a subset of the available equipment units. For the solution an outer problem involving the choice of campaigns. In a campaign the products are grouped in such a way that products in the same group do not use the same equipment units. After the outer problem has been solved an inner problem involving the solution of a mixed nonlinear program should be solved. This problem deals with choosing the number and size of equipment units needed. The key step linking the two subproblems is that of generating the most restrictive set of horizon constraints for each campaign taking into account direct production time and set-up time constraints.

The design of multipurpose batch plants is considered in more extent by *Suhami & Mah* [1982]. They state that the design problem of a multipurpose plant differs from the multiproduct plant design in that two or more products may be produced at any one time. Although successive batches of the same product may follow different routings, it is assumed that only one routing is permitted for each product. If more than one equipment unit is available of the same type they will all be assigned to the same product at one time to operate parallel out of phase. The equipment units of one type all have the same size. The problem is to choose the size and number of each equipment type such that production requirements are met within the horizon and such that capital investment is minimized. The constraints formulated resemble the constraints formulated by *Biegler, Grossmann & Reklaitis* [1988] for the multiproduct case. The multipurpose character is reflected by grouping products into campaigns which can be produced simultaneously. For these groups the horizon constraints are formulated. The objective is to find the campaigns which results in minimum equipment cost.

Several campaigns are generated randomly by choosing a product by chance and assigning it to the first compatible group. A group is compatible when the products in that group do not need the same equipment units. If no compatible group exists a new group is created. For each campaign the production sequence is determined (first group 1, then 2, etc.). The conflicts that exist between products in different groups that are produced successively are given in a graph. In this way a set of horizon constraints is formulated. Among the different campaigns generated the inferior ones are eliminated after a less constrained campaign is identified.

Among the remaining campaigns the best one is chosen according to a heuristic rule. With each horizon constraint a total product quantity can be calculated. For each campaign there exists one horizon constraint with the maximal quantity. The heuristic rule chooses the campaign with has the minimal value for the maximum quantity. After the best campaign has been determined the design problem is solved using the MINLP method.

The solution methods described above both consider two levels: on the higher level campaign formulation takes place, then on the lower level the optimal size and number of equipment units is calculated. *Jänicke* [1987] considers a single level solution method that is based upon solution methods for scheduling problems. By using a scheduling algorithm an initial solution to the design problem is found. Scheduling serves as a detector of bottleneck equipment, for which an additional equipment unit can be set. The changes in the initial design can be evaluated through the solution of the scheduling problem. *Jänicke* considers two ways to evaluate the design. First the completion time of the total of processing jobs. Secondly, the number of batches of equal type which can be produced simultaneously, which is interpreted as a measure for the flexibility of the plant.

To overcome the problem of having to solve the design problem for many different alternative campaigns *Vaselenak, Grossmann & Westerberg* [1987] propose a superstructure representation. This method requires the solution of a single MINLP problem similar to the problem of optimal design of multiproduct batch plants.

In the superstructure all product groups are embedded that can be produced simultaneously. First every two products that do not share the same equipment are grouped. Then it is examined of a third, fourth and so on product can be entered to the groups. As opposed to *Suhami & Mah* one product can be a member of several groups. Groups that become subsets of other groups are deleted. The remaining groups become the basis of the superstructure.

The problem of determining the optimal number of units and their capacities that minimize the total capital cost will be considered. The groups from the superstructure are produced in sequential periods, which leads to a multiperiod model. Not the production times of the individual products have to be equal or less than the horizon as in the design of multiproduct plants. In this case the length of periods in which a group of products is manufactured is used in the horizon constraints. A MINLP is formulated to solve the design problem for the superstructure. As mentioned before one product can be a member of more than one group and as a result be produced in several periods. In most cases the formulation can be simplified by merging the total processing times and total number of batches for each product, instead of defining these for each time period.

Barbosa Povoa & Macchietto [1993] consider the selection of both equipment units and the network of connections and storage facilities. The recipes for the products are represented by a maximal State Task Network. The state nodes represent the feeds, intermediate and final products. The task nodes represent the processing operations. In the network the allocation of tasks to equipment and products to storage vessels is given, as well as the connections between the states and tasks. A mixed integer linear program (MILP) has been formulated in which not only capacity, batch size and production requirement constraints are taken into account. Storage constraints and connectivity constraints are considered as well. As opposed to other design methods two design objectives are considered here; 1) the minimization of the capital cost for equipment and connections, and 2) the maximization of the plant profit.

3.4 Adapting the initial design: retrofitting
It has already been stated that in the batch process industry often low volume high added value products are being produced. A major characteristic of the markets in which batch

process businesses operate is that variation in product demand is high. Furthermore the products assortment changes quickly due to the introduction of new products and the removal of old ones. In this kind of market environment the ability to adapt quickly is necessary to survive. To respond to short term variations enough flexibility has to be available in the design. This calls for overdesign of process equipment in number and/or capacity; manipulation of operating variables and use of intermediate storage. Long term variations can be absorbed by allowing the possibility of later modification or expansion of the initial design.

Expansion has been incorporated into the design problem for multiproduct batch plants by *Wellons & Reklaitis* [1989a] as described in section 3.2. Three studies on retrofitting are presented of which two deal with multiproduct plants and one with multipurpose plants.

Espuña & Puigjaner [1989] consider the retrofitting of a multiproduct plant in which they determine the optimal class, placement, operation and sizing of the units to be added to the manufacturing process. An objective function is selected which takes into account only the extra plant investment costs and an expected overall net profit to be obtained from the additional production attained. The optimization is formulated as a mixed integer non linear programming (MINLP), which resembles the design method of *Espuña, Lazaro, Martinez & Puigjaner* in 3.2.

Vaselenak, Grossmann & Westerberg [1987] develop a MINLP for the optimal retrofit design of multiproduct batch plants. They consider the addition of parallel equipment in-phase to increase batch size, or out-of-phase to decrease cycle-time. The goal of the retrofit design problem is to maximize the profit of the batch processing plant, given new product demand and prices. The solution of the retrofitting problem will not be described here in more detail, because it resembles the solution of the design problem.

Papageorgaki & Reklaitis [1993] consider the retrofit problem of a multipurpose plant in two ways. First retrofitting to expand the capacity of the existing plant. A selection of the tasks that need more capacity has to be made and (nonidentical) processing units operating in and out of phase will be introduced. Second retrofitting to accommodate a revised product slate in the form of addition of new products, elimination of old products, or modification of existing products. In this situation one has to decide whether to add new equipment units and whether to remove existing equipment. *Papageorgaki & Reklaitis* [1993] develop a MINLP formulation for the deterministic retrofit design. Their model builds on models for the grass root design of multipurpose plants.

4. Allocation of production capacity

4.1 Planning and scheduling
According to *Hax* [1978] production planning is the discipline concerned with the allocation of production capacity and time; raw materials, intermediate product and final product inventories; as well as labor and energy resources so as to meet market demand for products over an extended period of time into the future.

In this definition the relation between the production and sales departments in companies is stressed. *Bertrand, Wortmann & Wijngaard* [1990] consider two main levels of coordination between Production and Sales. At the highest level, structural coordination takes place and long term global agreements are made. At an operational level the order acceptance function is performed which is primarily based on the availability of production capacity.

Another aspect of the definition is that planning concerns an extended period of time into the future. The detailed scheduling of process operations is usually a subproblem within overall production planning. There are two possible approaches to the overall production planning problem: single level and multi level. In the single level approach, both the overall production planning and the detailed scheduling are considered simultaneously. In the multilevel approach, the overall planning problem is decomposed into a hierarchy of subproblems. Commonly a long or medium term planning subproblem is considered and a short term scheduling subproblem [Ku, Rajagopalan & Karimi, 1987]. The short term scheduling subproblem has received considerably more attention than the medium term production planning.

To solve the scheduling problem several objective functions can be used that minimize the makespan, the mean or maximum flow time, the mean or maximum tardiness or the changeover and setup costs. Flow time is defined as the time required to pass completely through the process. Tardiness is the difference between the delivery date and the due date when a product is delivered after the due date.

To make a schedule for batch plants the possibilities of intermediate storage are of importance too. The four possibilities are unlimited intermediate storage (UIS), finite intermediate storage (FIS), no intermediate storage (NIS) and zero wait (ZW).

The scheduling problem is a NP-complete problem, which means that they become very hard to solve. Calculating times increase rapidly as the complexity of the problem increases. For large problems (many products, processing steps and capacity units) only suboptimal solutions can be obtained.

In this section both single and multi level approaches to production planning and scheduling are presented. Multi product batch plants are considered first, followed by planning and scheduling in multi purpose batch plants.

4.2 Planning and scheduling in multiproduct batch plants
For the scheduling of a multiproduct plant a heuristic method was formulated by *Biegler, Grossmann & Reklaitis* [1988]. Their problem involves a network of processing units, with identical parallel units, a known number of batches of each of the products to be processed, a specified set of stage transfer rules, a fixed processing time matrix, and possibly a matrix of change-over times. The first step consists of the creation of an initial ordered product list, for instance ordered by the total processing time. When two or more parallel production lines are available the products are assigned to a line, for instance by using the earliest finish time criteria. A product is assigned to the line which yields the earliest finish time for the products already assigned plus the product being assigned. The line sequences are constructed using Johnson's rule which is well known in scheduling discrete manufacturing.

Kuriyan & Reklaitis [1989] consider scheduling of a multiproduct plant with parallel equipment units and two transfer rules: unlimited intermediate storage (UIS) and zero wait (ZW). The objective is to minimize the makespan. A two-level approach is used. At the upper level a processing sequence is determined that assigns products to units and also determines the order in which products are processed on any unit. At the lower level a sequence evaluation algorithm calculates the completion times for each product on each unit.

Four types of sequencing methods are regarded at the upper level:
1. Dispatching rules: for instance "longest processing time first" (LPT), "shortest processing time first" (SPT), and "earliest due date first" (EDD).

2. Bottleneck sequencing: Every stage in turn is considered a bottleneck. The scheduling problem is reduced to a single-stage or two-stage process by relaxing capacity constraints for all stages except "bottleneck" stages. For each subproblem a sequence is found using a heuristic rule.
3. Local search sequencing: Given an initial sequence, a local search method searches through all the sequences that belong to its neighborhood, for example by exchanging two products. The best sequence replaces the initial sequence, and becomes the starting point of the next iteration.
4. Best fit sequencing: This is a form of local search in which the best place to add a new product to an existing partial sequence is sought. The difference with local search is that it does not start with a complete processing sequence, but with a partial sequence.

From test it is concluded that best fit and local search methods provide the best sequences. Bottleneck sequencing methods are more effective than dispatching rules, but less effective than local search methods.

At the lower level the sequence evaluation procedures are of two types: "one product at a time" (PAT) or "one stage at a time" (SAT). The difference in schedules produced by these methods is small. However, the PAT method is more flexible since it can be used for both ZW and UIS networks. In case of ZW restrictions it is not possible to use SAT.

Abad, Espuña & Puigjaner [1991] present a strategy for task scheduling and optimum production planning of textile fiber manufacturing. The strategy consists of three steps:
1. A feasible point is reached by straight forward application of delivery times and utility priorities on one hand, and technical constraints verification on the other.
2. The optimization procedure tries to minimize the objective function value by using three main tools: simulation, an ad-hoc scheduling procedure, and a task rescheduling algorithm.
3. Once verified all changes leading to objective function improvements, the rigorous optimization step takes place. Implicit enumeration of all possible job-to-line assignments is made. Then, checking and simulation is done, taking into account all possible ordering within line, for each assignment already made.

4.3 Planning and scheduling in multipurpose batch plants
A production planning procedure for multipurpose plant was developed by *Mauderli and Rippin* [1979]. The procedure whereby equipment units are assigned to process tasks can be divided into a number of stages, namely:
1. The generation of alternative batches for each of the products.
2. The combination of the batches of each product into alternative production lines of that product.
3. The generation of alternative campaigns using non-overlapping production lines of one or more products in parallel.
4. The screening of campaigns to identify dominant, that is to say efficient, campaigns.
5. The construction from the dominant campaigns of a production plan by a linear optimization procedure.
First all possible batches with one equipment module assigned to each processing step are generated by a depth-first enumeration procedure. A batch represents one possible routing for a product. The batch size for each possible batch can be increased, if more capacity is supplied at the limiting step. This can be done by connecting one or more additional equipment items, in parallel, at that step. The next step is to eliminate inefficient batches. If the same set of equipment units is used in a different configuration to produce the same product, only the configuration with the largest batch size is retained. If an equal or larger

batch size can be obtained with a subset of the equipment units used for a given batch in a different configuration, then that batch is eliminated.

The batch procedures are combined into production lines. A production line is a sequence of consecutive batches of one product. If processing times for some steps are much greater than for others, it may be possible to combine two batches using different equipment in parallel out-of-phase for the longer steps, and the same units for the shorter ones. Performance of these production lines must be assessed by calculating the sequence cycle times and average output rates. Different production lines may contain the same equipment, but arranged in a different way. In such a case, only the production line having the highest output rate of product per unit time is retained. Further, any production line is rejected if an equal output rate can be obtained with a subset of the equipment.

A campaign is a set of production lines producing the same or different products. During a campaign, each item of equipment in the plant is either assigned to a specific task in one production line or is idle. All feasible campaigns containing one production line for each of the products in the combination are considered as 'starting solution'. A single product campaign is stored for further use if its output rate is greater than that of any campaign previously considered for that product. A campaign of two or more products is a candidate for consideration as a dominant campaign, if its average output rate is greater than could be achieved by operating the best single product campaigns.

A linear programming procedure can determine which dominant campaign should be implemented, and the time allocated to them, for maximum profit or minimum time to meet specified product requirements [Mauderli & Rippin, 1980].

The scheduling problem for multipurpose batch plants is treated by *Egli & Rippin* [1986]. They state that the problems which can be treated by the existing procedures are much more restricted than the typical day-to-day scheduling problems commonly found in multiproduct batch chemical plants. The distinctive feature of the scheduling system presented lies in the variety of realistic constraints which can be incorporated: multistage production processes, stable and unstable materials with consequences for intermediate storage, resource utilization constraints, product interdependence, time and cost of product changeovers, stock holding cost, working patterns, product requirements.

According to *Egli & Rippin* [1986] a dynamic procedure for short-term scheduling is essential to adapt to changes in the scheduling situation. These changes can be external, like receiving new orders, changes in material supplies or changes in working time or condition. Changes within the plant can also occur, for example changes in the availability of equipment, production delays and changes in the quality of materials and (intermediate) products.

The situation is considered in which production requirements are available over a short period of time. Given the due dates and the available capacity a feasible production sequence should be found. Delays in meeting orders is only accepted on material availability grounds. The scheduling procedure described consists of enumeration of all possible sequences, elimination of non-feasible and non-optimal sequences and the full evaluation of a few favorable sequences.

The determination of the best production schedule consists of nine stages:
1. Construction of independent product groups, which do not share the same intermediate products and equipment units.

2. Construction of a priority list. First on the list are end products, followed by products one step removed from end products, etceteras.
3. Division of the production alternatives into stable blocks, which can be shifted to satisfy working time and capacity constraints.
4. Enumeration of feasible production sequences for each independent product group. Taken into account are final product demands, delivery dates, capacity availability and storage constraints.
5. Shift to latest production time to decrease storage of final products.
6. Backward shift of batches or stable blocks to meet constraints arising from restricted working times and limited resources.
7. Check on raw material deliveries. If production is constrained by shortage of raw materials the production schedule is shifted forwards to the point at which raw materials become available.
8. Costing of accepted production sequences. Changeover cost, cost of the utility requirements and penalty cost for any infringement on the safety stock is calculated.
9. Output of the solution. The sequence is chosen which results in minimal cost.

In contrary to the importance they put upon dynamic scheduling, the method presented by *Egli & Rippin* [1986] is not dynamic itself. It starts with a given set of product requirements that should be met in a certain time period.

Rich & Prokopakis [1986] present a mixed integer programming model for a multipurpose batch plant. The purpose of the model is to select the number of batches of saleable and intermediate products to be produced in a production run so as to satisfy customer demand over the planning horizon. The availability of sufficient storage capacity is assumed. No storage costs are considered and change over times are sequence independent. The number of batches and the start times of these batches are determined so as to minimize a certain objective function. This can be the mean or maximum tardiness, mean completion time, makespan, idle time on all processors or on one specific processor. The constraints which are taken into account are precedence constraints; for instance intermediate products must be available before starting a production run, demand constraints, production limitations established by reactant availability, and disjunctive constraints which are necessary because only one operation can be processed simultaneously in a reactor unit. Two test problems were solved by the mixed integer model. The first case consisted of two end products, three intermediate products and two processor. The second case, however, was somewhat more complicated. It considered ten end products, two intermediate products, and 43 processors. For the latter test case an optimal solution was obtained after 4.87 CPU s.

The multipurpose plant scheduling problem is also studied by *Wellons & Reklaitis* [1989b, 1991]. The scheduling problem is decomposed into three subproblems: production planning using some set of alternative campaigns, the generation of the set of alternative campaigns from an existing set of equipment items, and the scheduling of the single-product production lines of which the campaigns are composed.

For the single-product scheduling problem first the path sequence on which batches are to be produced and the path batch sizes are determined. Second the schedule of operations for each unit of the production line including processing time, transfer or overlapping time and holding time for the path sequence is determined. A MINLP formulation is used to maximize the processing rate of the production line.

4.4 On-line rescheduling
After the production orders are scheduled the execution phase starts. This introduces varieties in for example set-up and production times which results in delays or advancements. The use

of a fixed off-line schedule to operate a variable plant can result in two major effects. First, the time spent by batches waiting for processing units to become available may increase and secondly, the idle time of the processing units may increase [Cott & Macchietto, 1989a]. If the actual processing time of a task is longer than the scheduled one, then processing units are blocked and the wait times of batches are increased. If the actual processing time is shorter, the idle time of the processing units is increased and equipment underutilization may occur.

These operating problems can be overcome by dynamically modifying the start times of the schedule but not-yet-executing batches. Because the rescheduling algorithms will be run in real- time as part of a computer-aided operating system, the algorithms cannot be overly complex or time consuming to run.

There are three types of modifications: shift delays, shift advances and shift both. The simple shift modification algorithms do not provide as good a performance in terms of the long run averages of the total time taken to process a batch and of the amount of time between the start of two consecutive batches on the first unit. This is because they only consider local information and fail to incorporate sufficient detail about future consequences of changing start times. Therefore *Cott & Macchietto* [1989a] developed the projected operation modification algorithm (POMA). This algorithm involves estimating ahead in time, from the current operation, the expected completion times of all executing batches.

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