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W.H.M. Raaymakers*

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* Faculty of Technology Management
Eindhoven University of Technology
P.O. Box 513, Paviljoen F10
NL-5600 MB Eindhoven
The Netherlands
Phone: +31.40./2473949/2472230
E-mail: w.h.m.raaymakers@TM.TUE.NL

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Wenny H.M. Raaymakers
Eindhoven University of Technology
Eindhoven, The Netherlands

ABSTRACT

Multipurpose batch process industries often operate in markets for low volume, high value added products with a variable and dynamic demand. Therefore, production should offer extensive flexibility. Production occurs on general purpose equipment, which is formed into configurations to produce a product or product family. In this paper it is discussed that businesses in the multipurpose batch process industry need a practical method for medium and short term capacity planning in order to be able to realise both sufficient utilisation of the available capacity and a high delivery performance. It is discussed that methods available in the literature are not very well suited for this. Therefore a research agenda on planning in multipurpose batch process industries is proposed.

INTRODUCTION

In the process industry one finds a large variety of businesses. A distinction can be made between process/flow and batch/mix businesses [Fransoo & Rutten, 1994]. The first type produces generally high volume, low value added products. The investments in production capital are very high, which makes it necessary to maintain a high (close to 100 %) utilisation. In the batch/mix industries low volume, high value added products are produced. Relatively general purpose equipment can be used to produce these products, and investments in capital are far less than in process/flow industries. The processes in batch process industries are less well controlled than in flow industries and automation of processes is less far reaching. Batch process industries are flexible both in the products and in the volume that can be produced.

In batch process industries a distinction can be made between multiproduct and multipurpose batch process industries. When the products all follow the same sequence of processing steps along the equipment units (routing), it is defined as a multiproduct plant. However, when different products have different routings and sometimes even one product has several alternative routings, it is called a multipurpose plant [Rippin, 1991] [Reklaitis, 1990]. In this paper attention is paid to multipurpose batch process industries.

When a comparison is made with discrete manufacturing, multipurpose batch process industries have many features in common with discrete job shops. Either one generally produces a large variety of different products with high demand uncertainty. The products generally have different routings and are produced on a set of general purpose equipment. A classification of industries in which the similarities between process and discrete manufacturing are visible, is given by Puttman (1991). In table 1 this classification is shown with some examples of industries. The distinction between process/flow and batch/mix is reflected in the table by a process flow shop and a process job shop respectively.

Table 1: Logistic Similarity by Puttman (1991)

	Process industry	Discrete Industry
Flow shop	starch salt fertilisers surfactants	matches cigarettes electronics tires frozen chickens
Job shop	pharmaceuticals flavors convenience food fragrances	furniture bicycles prefab buildings video, audio

However, there are also some important differences between discrete job shops and multipurpose batch process industries. The first difference concerns the relation between succeeding processing steps. In discrete job shops it is generally possible to form queues of work in process in front of equipment units. In process industries the storage of intermediate products is generally more limited. This is related to the stability of intermediate products and the need to store the intermediate products in vessels or containers. Furthermore in process industries the equipment units, on which succeeding processing steps are carried out, often need to be coupled by pipes.

A second difference concerns the fact that in batch process industries production takes place in discrete batches. Because of this, time and volume utilisation of the equipment units is split. In many cases the processing time does not have a linear relationship with the batch size. This can best be explained using an example. When a mixing vessel with a capacity of 1000 litres is filled with only 100 litres, the time to mix 100 litre can very well be equal to the time to mix 1000 litres. Whether the vessel contains 100 or 1000 litres does not matter for the availability of that vessel; it can not be used for another product at that time. More-over, the relationship between processing time and output is often not linear for a given input. For example in chemical reactions where after a period of time an equilibrium is found.

In this paper, we will discuss that research is needed on planning in multipurpose batch process industries. We will illustrate that the available models and techniques from the literature are not very well suited to be applied to realistic planning problems. Therefore, first the characteristics of multipurpose batch process industries are described. Then the planning difficulties will be discussed. Next, the available literature on planning and scheduling in multipurpose batch process industries will be discussed. We conclude by addressing the current shortcomings and argue that a hierarchical approach towards these problems may lead to better practice.

CHARACTERISTICS OF MULTIPURPOSE BATCH PROCESS INDUSTRIES

Multipurpose batch plants generally produce a large range of different products. The demand for these products is usually highly variable and dynamic. The product assortment changes relatively quickly. It is therefore very difficult to provide accurate and reliable demand forecasts.

Production is carried out on relatively general purpose equipment. This provides the possibility to produce a range of different products. The investments in capital are far less than in process/flow industries. Compared to process/flow industries, the processes in batch process industries are less well controlled and automation of processes is less common. Normally operators are an important resource which is shared by the capacity units.

Production occurs in discrete batches. The equipment units are vessels of some kind in which for example mixing, heating and/or chemical reactions take place. Because of the discrete batches there is a distinction between time utilisation and volume utilisation. When several succeeding processing steps take place in different equipment units one has to take into account the batch sizes of all the equipment units involved. The batch size is limited by the equipment unit that can handle the smallest batch. It is possible to adapt the batch sizes to the limiting batch size, but it may be possible to split and merge batches and produce them in parallel. Another possibility is to partly decouple the processing steps by introducing intermediate storage. The processing times in some cases depend on the batch size, but not in all cases. Furthermore, the batch time is limited by the processing step that takes the longest time. When several consecutive batches of the same product are produced, the number of batches produced per time unit depends on the longest batch time. Batch sizes do not only have a maximum, sometimes it is restricted to a minimum as well. For example a mixing vessel has to be filled to a certain level to be able to stir well.

In batch process industries the possibilities for intermediate storage are generally limited. Four rules for transferring intermediate products between processing steps can be distinguished [Biegler et al., 1988]. The first rule applies to situations where the intermediate product is not stable and has to undergo the next processing step without delay. This is called Zero Wait (ZW) transfer. The second possibility is No Intermediate Storage (NIS), when intermediate products remain in the equipment unit until the succeeding unit becomes available. The third rule is Fixed Intermediate Storage (FIS) when a limited number of storage vessels of a specific volume is available. The fourth rule is Unlimited Intermediate Storage (UIS). In business practice often all four transfer rules are found at different stages and for different products.

In multipurpose batch plants the equipment units are usually grouped into temporary configurations to produce a specific product or product family. A configuration is a set of equipment units forming a production line. The equipment units on which succeeding processing steps take place are often coupled by pipes, which are needed to transfer the intermediate products. After production of that product family has finished, the equipment units are grouped into another configuration. Products that use nonoverlapping configurations can be produced simultaneously. Equipment units that are not included into a configuration at a certain moment are unavoidably idle.

A final characteristic of batch process industries, considered in this paper, is that set-up times and cleaning times usually have a considerable impact. The set-up and cleaning times often take only a few hours and are very short compared to process/flow industries. However, because of the many different product that are produced and the short production runs for each product the total time spend on setting up and cleaning the equipment units is considerable. In many cases the set up and cleaning times are sequence dependent. Total set up and cleaning times can be decreased when this is taken into account.

THE PLANNING PROBLEM

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 labour and energy resources, so as to meet market demand for products over an extended period of time into the future [Hax, 1978]. Planning has to deal with several goals: realising short and reliable delivery times and producing efficiently by realising a good utilisation of the available capacity.

The utilisation of capacity in multipurpose batch process industries is generally low. Often some bottleneck units can be identified, but these are not necessarily stable over time. In the batch process industry a distinction between time and volume utilisation should be made. The time utilisation reflects the time an equipment unit has been used for production in relation to total production time. The volume utilisation reflects the production batch size related to the maximum batch size. This distinction is important because in many cases the processing time is independent of the batch size. In these cases the time utilisation does not change when the batch size is changed, because the processing time remains the same.

The low utilisation of equipment is partly a result from the production in configurations. Not every equipment unit can be part of a configuration at any time. Therefore, when a certain equipment unit has a low utilisation rate this does not necessarily mean that more products can be produced with this equipment unit. It is possible that the equipment units that need to be used in combination with this particular equipment unit are not available. Because of the existence of nonoverlapping configurations the production efficiency is related to the combination of several nonoverlapping configurations into a campaign. Some combination of different products can be produced more efficiently in parallel, than other combinations. Furthermore, the production efficiency is influenced by sequence dependent set-up times.

The main problem in planning multipurpose batch process industries is that it is very difficult to estimate the available capacity over a medium term horizon. This is caused by the number of different configurations which can be used to produce the different products. Because of the need to produce with a set of equipment units, the utilisation rates of the individual equipment units do not give appropriate information on whether a certain product can be produced. When the individual equipment units have sufficient time left to produce a product within the time horizon, it does not necessarily have to be the case that a time period can be found in which all equipment units are available.

Medium term capacity planning is essential for three reasons. First, to be able to form efficient campaigns. As was stated earlier, for production the equipment units are grouped into temporary configurations. The equipment units included in a configuration are generally coupled by pipes. An equipment unit is at any moment part of one configuration or is idle. Products that use nonoverlapping configurations can be produced simultaneously. In multipurpose batch process industries there is generally a large variety of different routings. The consequence is that some products can be produced simultaneously and others can not. When taking this into account one can form campaigns of products with nonoverlapping configurations. In this way efficient campaigns can be formed, which will decrease the number of capacity units being idle necessarily. This will provide the possibility to increase overall production output. When sequence dependent set-up and cleaning time are considered to determine the sequence of campaigns, a further increase in production efficiency can be reached.

A second reason for medium term capacity planning is to support customer order acceptance. The large variety of different products and routings, together with the intermediate storage constraints provide a complex capacity structure. To produce a certain product a set of equipment units is needed at the same time to form a configuration. Therefore the utilisation of the individual capacity units does not provide all the information to accept customer orders. Here the situation is meant in which the individual capacity units have sufficient production time available over a certain time period, but are not available at the same time. In that case it is not possible to set up the required configuration. This will generally provide problems in producing the product concerned. When campaigns are formed on a medium term, this will provide a better insight into the available production capacity. In the campaigns the need to produce in configurations, rather than with individual capacity units, is taken into account. The customer order acceptance function is of special importance to batch process industries, because there is generally a high demand uncertainty. Periods of relatively low demand are followed by periods of high demand. The customer order acceptance function provides the possibility to smooth out the variation in demand. This does not only concern the acceptance or rejection of a customer order, but also setting the agreed delivery date.

A third reason is to support decisions considering increasing overall production capacity or contracting out. As was said earlier businesses in batch process industries face a high demand uncertainty. In periods of high demand there are generally several possibilities to increase production capacity. First, additional capacity units can be acquired. This is, however, a strategical decision and is generally not taken at the medium term level. Second, additional operators can be hired. In many instances this will increase the overall production capacity. It also provides the possibility to increase the number of shifts. This measure will not be appropriate in cases where the availability of certain capacity units is the bottleneck, and when production takes place year round. In that case there is a third possibility, namely to contract out a part of production.

LITERATURE REVIEW

In this section the available literature, which consider both medium and short term planning in multipurpose batch process industries, is discussed. In general these methods consist of campaign formulation and detailed scheduling.

A production planning procedure for multipurpose plants was developed by *Mauderli and Rippin* [1979, 1980]. Their procedure, which assigns process tasks to equipment units, can be divided into five stages. First, alternative batches for each of the products are generated by an enumeration procedure. In their definition, a batch represents one possible routing for a product. The batch size for each possible routing 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 in phase, at that step. Next, inefficient routings are eliminated. 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 product in a different configuration, then the less efficient configurations are eliminated.

In the second stage the remaining routings of each product are combined into alternative configurations of that product. With a configuration a sequence of consecutive routings of one product may be produced. If processing times for some steps are much longer than for others, it may be possible to combine two routings using different equipment in parallel for the longer steps, and the same units for the shorter ones. Consecutive batches will undergo the longer processing step on either one of the parallel units. Performance of these configurations must be assessed by calculating the sequence cycle times and average output rates. Different configurations may contain the same equipment, but be arranged in a different way. In such a case, only the configuration having the highest output rate of product per unit time is retained. Further, any configuration is rejected if an equal output rate can be obtained with a subset of the equipment.

Third, alternative campaigns are generated, using non-overlapping configurations of one or more products in parallel. A campaign is a set of one or more configurations not using the same equipment, which can therefore be operating simultaneously. During a campaign, each equipment unit in the plant is either assigned to a specific task in one configuration or is idle. As a starting solution only single product campaigns are considered. For each product the single product campaign will be remained that generates the highest output rate. Next, campaigns of two or more products will be considered. These will become candidates for consideration as a dominant campaign, if its average output rate is higher than could be achieved by operating the best single product campaigns.

During the fourth stage the campaigns are screened to identify dominant, that is to say efficient, 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. Finally, a production plan is constructed from the dominant campaigns by a linear optimisation procedure.

A comparable approach is given by *Lazaro, Espuna & Puigjaner* [1989]. With a given product demand pattern they determine an optimal solution, taking into account plant limitations like available equipment, storage and product changeovers. The solution method consists of the following steps. First, the batch plants and processes are characterised by obtaining production capacity and operating times. Both batch and semi continuous equipment can be taken into account. In the next two steps all possible production sequences are enumerated and dominant configurations are selected by a heuristic rule. This rule is based on three parameters, concerning the processing capacity per unit time, the idleness of the equipment used in a configuration and the production cost divided by the processing capacity. In the fourth step a schedule is determined using a heuristic strategy that minimises the makespan. Finally an algorithm is used to set an optimal production plan which considers real life restrictions concerning processing time, utilities and storage facilities.

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 minimise 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, demand constraints, production limitations established by reactant availability, and disjunctive constraints which are necessary because only one operation can be processed simultaneously in an equipment unit. Two test problems were solved by the mixed integer model.

The multipurpose plant scheduling problem is also studied by *Wellons & Reklaitis* [1989, 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 units, and the scheduling of the single-product configuration 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 configuration including processing time, transfer or overlapping time and holding time for the path sequence is determined. A MINLP formulation is used to maximise the processing rate of the production line.

A different approach is chosen by *Patsidou and Kantor* [1991]. They studied a multipurpose batch plant that operates in cycles in which for each product one or more batches are produced. It is assumed that the same cycles are repeated. The sequence of tasks that is performed on the available equipment units in one cycle is called an operating policy. All possible operating policies are enumerated and examined using minimax algebra. The one with the minimum cycle time is the optimum policy.

Papageorgiou & Pantelides [1993] propose a method for hierarchical campaign planning that takes account of flexibility of intermediate storage and equipment reuse. They consider multipurpose batch plants for which reliable long-term demand forecasts are available. The method presented determines the number and timing of campaigns and the operating schedule of each campaign over a given time horizon, so as to maximise the total value of production over the horizon and satisfying the minimum production amounts for each product. The method consists of three steps. In the first step a feasible solution is found using the algorithm of *Shah & Pantelides* [1991]. In the second step for each campaign a detailed schedule is derived, taking account of the minimum amount of each product needed over the time horizon. Furthermore, in this step the production rates are improved. In the last step the timing of the campaigns is considered, attempting to maximise total production value.

Subrahmanyam et.al. [1995] use a decomposition strategy to solve planning and scheduling problems in batch plants. First the MILP formulation used for designing batch plants, called the Design Super Problem (DSP), is reduced to a LP formulation for planning. Because of the aggregation in the DSP not necessarily a feasible schedule is yielded. Therefore a detailed schedule is determined by a MILP. When infeasibility is identified its effect is attributed to the DSP. The excess batch sizes, indicating the batch size required to make the problem feasible, is calculated. Next the forced downtime of equipment units is determined and used in the DSP as the time the unit cannot be used. In an iterative way a feasible solution is obtained.

HIERARCHICAL PLANNING

The methods discussed in the literature suggest the availability of detailed and accurate information. Given the demand for the products optimal or near-optimal campaign formation and a production schedule is determined. This assumption is the most important limitation of the available literature. Multipurpose batch plants are characterised by a dynamic environment. Demand for the products varies considerably over time. Often only for a very short time period detailed information on customer orders is available.

Besides the uncertainty of demand there are several other uncertainties that are of influence. For example changes in material supplies, changes in the availability of equipment and operators, delays in production, changes in quality of materials and (intermediate) products possibly resulting in changing processing tasks. This dynamic environment in practice results in schedules that have to be adapted frequently. When production of a certain product is delayed, this means that succeeding campaigns will be delayed as well. Due to the production in campaigns a delay for one product, will generally have an impact on several other products. There is also a need to adapt the schedule when limited storage is available. When intermediate products can be stored, the number of storage vessels is generally limited. In business practice production is sometimes constrained by the availability of storage vessels. Therefore, the usage of these vessels should be included in the production schedule. Delays in production for one product sometimes result in delays for other products, because the required storage facilities are not available. When a detailed production schedule is obtained for medium term time periods, this will result in many adaptations of the schedule. Therefore, detailed scheduling is of limited use on the medium term.

The presented literature is limited to restricted problems. In several cases it is assumed that only one routing is possible for each product or that there are alternative equipment units, but that these are all identical. In practice there often exists a limited interchangeability between equipment units. Units belonging to one group or type often differ in size and in some technical specifications. For example the pressure or temperature that can be obtained, the availability of special precautions to be able to handle aggressive chemicals. Furthermore, the theoretical models often assume that only one intermediate storage policy is available; either zero wait, no intermediate storage, fixed intermediate storage or unlimited intermediate storage. In practice these policies often exist together in one plant.

In the literature no attention is paid to the customer order acceptance decision. In multipurpose batch plants it is very hard to get a clear view on the available capacity, due to the large amount of different products and routings and the necessity to form configurations of equipment units to produce certain products. A medium term campaign planning would provide information which can be used to decide upon accepting customer orders and set delivery times. In practice most of the time all incoming customer orders are accepted, which results in a low delivery performance in periods with high demand.

When the characteristics of multipurpose batch plants are taken into account, and the available literature on planning and scheduling is considered, we may conclude that the available models and techniques from the literature are not very well suited to be applied to realistical problems. Also, the limited availability of accurate data severely limits the application of these approaches. Therefore, in this research we aim at finding a hierarchical production planning method with practical relevance. This method will consist of medium term campaign planning and short term production scheduling.

The campaign planning aims at realising high production efficiency, by determining which products can be produced simultaneously and consecutively in an efficient way. For determining which products can be produced simultaneously the idleness of equipment units, which are not included into a configuration, will be used as a measure of efficiency.

For determining which products will be produced consecutively the total time spent on cleaning and set up will be used as a measure of efficiency. This is based upon the fact that cleaning and set up times are generally sequence dependent. The total time spent on cleaning and set up is considerable, because of the production of many products in small batches.

For the campaign planning, groups of similar products instead of the individual products will be considered for two reasons. First, it is expected that groups of products will have more stable demand characteristics than individual products. On the medium term, only aggregate and unreliable information is available. Therefore the use of product groups will lead to a medium term planning that is more robust than a planning based on individual products. Second, the size of the planning problem will be reduced when groups of products are considered. This reduction will result in a better insight into the planning situation. This insight may be used to support the customer order acceptance decision.

The products will be grouped on the basis of routing and demand similarity. Products that use the same configuration of equipment units are put into the same group. Different product groups may have some equipment units in common. On the medium term capacity will be allocated to product groups instead of individual products. Because of the use of product groups trade-offs between products will become more clear. When a certain group claims more capacity this will result in less capacity remaining for an other group. This is especially important when both groups use a bottleneck equipment unit. If individual products are considered, an increase of production for one product can result in less capacity remaining for many other products.

In discrete parts manufacturing a lot of research has been done on forming groups of products. Group technology (GT) is based on similarities in design and manufacturing characteristics between parts. The main advantages offered by GT in discrete manufacturing include lower set-up times, reduced lot sizes, lower lead times, and easier production planning and control [Kaku & Krajewski, 1995]. Because of the generally fixed batch sizes and the limited possibilities for intermediate storage it is expected that not all these advantages will apply to batch process industries. However, it is expected that lower set-up times and easier production planning and control can be realised. Reduced planning complexity is especially important because batch process industries are significantly more complex than discrete job shops due to the limited storage possibilities and the need to couple capacity units by pipes. In GT groups are formed on the basis of classification and coding and production flow analysis in which rank order clustering, similarity coefficients and cluster identification algorithms are used [Perrego, Petersen & Hahn, 1995].

Campaign planning will lead to a loss of flexibility on the short term. However, this loss will be less than when detailed scheduling is used for medium term planning. Because the campaign planning will be based on product groups instead of individual products there will be sufficient flexibility available within these groups. Furthermore the trade offs between groups will be clearly visible. When a certain capacity unit is used by more than one group an increase in demand for one product group has an impact on the available production capacity for the other groups.

When on the medium term a campaign planning is obtained, a detailed production plan for the short term can be determined. On the short term it is decided which product should be produced within a given campaign. The product groups, which are used for the campaign planning, generally consist of products with similar routings. Within the campaigns the sequence in which the products of one group should be produced has to be determined.

SUMMARY

Multipurpose batch process industries generally produce a large variety of low volume, high value added products with a variable and dynamic demand. These products follow different routings through the plant. Production occurs in batches and is generally carried out on general purpose equipment. Intermediate storage is generally restricted, due to the intermediate products not being stable or the limited availability of storage capacity. Equipment units often need to be coupled by pipes to be able to transfer the intermediates. Therefore, so-called configurations of equipment units are used to produce a certain product or product family. Products that do not need the same equipment units can be produced simultaneously in nonoverlapping configurations. This is referred to as a campaign.

We have demonstrated that medium term capacity planning may be useful to determine efficient campaigns and the sequence in which campaigns should operate. At this point one should consider which products can be produced simultaneously. Furthermore, the cleaning and set up time should be considered when proceeding from one campaign to the subsequent campaign. Medium term capacity planning will also support customer order acceptance by providing a better insight into the available capacity.

Planning methods for multipurpose batch process industries, available in the literature, are not very well suited to be applied to realistic problems. They generally consider deterministic cases in which detailed and accurate demand and production data are available. In multipurpose batch plants this is generally not the case. Both demand and production uncertainty is high. Besides that, real life situations are much more complex than the situations considered in the literature. Furthermore, the available methods do not consider the acceptance of customer orders.

Research is needed on capacity planning in multipurpose batch process industries that will lead to a method with practical relevance. A hierarchical method that considers both medium term campaign planning and short term scheduling will be developed. Methods available from discrete manufacturing, like group technology, will be used in developing a planning method for multipurpose batch plants.

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