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Demand Management and Production Control in Process Industries

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Introduction

Process industries cover a wide range of businesses. The American Production and Inventory Control Society (APICS) uses the following definition:

> Process industries are businesses that add value to materials by mixing, separating, forming or chemical reactions. Processes may be either continuous or batch and usually require rigid process control and high capital investment[1].

Usually this will include the production and/or procurement of food products, paper and cardboard, chemicals, crude oil, rubber and plastics, synthetic and artificial threads and fibres, building materials, pottery and glass, primary metals and energy[2].

According to the definition presented by APICS, a distinction can be made between two different kinds of process industries, namely batch process industries and flow process industries. Batch process industries are characterized, in general, by several process steps, different products routeings, a mainly convergent materials flow ("assembly"), and a high added value. Examples of these industries are: pharmaceutical and other fine chemical industries. Flow process industries are characterized by: one (or very few) process steps, the same process routeing for all products, a divergent materials flow, and a low added value. Examples of these industries are: bulk chemicals, glass manufacturing, paper production and steel moulding. In our research we will focus on flow process industries[3].

During the last decades a tendency towards larger-scale production sites can be observed in process industries. Installations have become larger and more dedicated (caused by the integration of processes), and set-up times have increased. Profits were good during many years, but at the end of the 1970s the market changed. Product variety increased, while order size and required delivery time decreased. Planning algorithms have not been able to deal with these changes. Furthermore, the environment has become so dynamic that any schedule found to be reasonable, soon changed into an invalid one.

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Given the general characteristics of the flow process industries environment, the production control problem addressed here can be characterized by multiple different products, a single machine, high set-up times, a high production speed/selling speed ratio per product and a divergent materials flow.

As the production installations are very expensive, a high utilization is required to maximize the throughput. In practical situations, we have seen these installations being used up to 100 per cent of net capacity. Net capacity is then used either for production or for setting up. Also, it is impossible to increase the capacity availability in small steps, because overtime is not available (round-the-clock production). A shutdown is usually only done once in a very long time period, for maintenance reasons. In a glass factory, for instance, an oven is overhauled once every seven years. Adding another installation to the system could easily double the available capacity. Due to these factors, the demand level is usually very close to the available production capacity.

The purpose here is to develop a general planning and control model for process industries. To develop the framework we will first analyse the available literature regarding the single machine multi-product scheduling problem. This analysis will be supported by simulation experiments which test the application of a published heuristic in a situation with very high demand. From these experiments, it will be concluded that it is an important design objective for the planning framework to focus on stable cycle times. Based on this design guideline, the model will be developed. Finally, managerial and organizational implications of the model are discussed.

Review of Academic Literature

Theoretically, the problem can be characterized as a single machine multi-product scheduling problem, with high set-up times. Numerous articles on sequencing and scheduling a single machine have been published in the literature. The majority of these papers refer to deterministic situations. Elmaghraby[4] has presented a review of the so-called Economic Lot Sizing Problem (ELSP), which focuses on determining batch sizes. He summarizes the basic data of the problem as follows:

- demand rate is deterministic
- production rate is fixed (and larger than the demand rate)
- set-up time and set-up cost are independent of sequence
- backlogging of demand is not permitted.

Elmaghraby distinguishes two kinds of approaches: those which accept the concept of a basic period (or cycle time) and those which do not. Cycle time is then defined as the amount of time between the start of two consecutive production runs of the same product.

More recently, Gupta and Kyparisis[5] have presented an extensive review, which focuses on the problem of scheduling a number of given jobs (lot size and due date are given). In the majority of the papers in their review (over 200), the deterministic assumption is prevalent.

The category of papers reviewed by Elmaghraby contains theory which might be usable to construct heuristic algorithms for stochastic situations. Leachman and Gascon[6], however, have shown that these heuristics (e.g. the one presented by Doll and Whybark[7]) do not lead to satisfactory results in stochastic situations. Consequently, in their article, Leachman and Gascon present a heuristic for situations with a stochastic demand. Their heuristic is a period-based heuristic, which tries in each review period to achieve a target cycle time. This target cycle time is calculated based on an economic manufacturing quantity (i.e. a trade-off between inventory holding costs and set-up costs). If this target cycle time does not lead to a feasible schedule in the short run (one or more products run out of stock), then the cycle time is decreased. In this way, production runs can be started earlier to increase the (short-term) service level. the total decrease of the operational cycle time is limited by the so-called minimum run length (*m*). The length of a production run can never be shorter than *m*. We will call this kind of heuristics Variable Cycle Times (VCT) heuristics.

A description of the variable cycle times heuristic that we have implemented in our tests can be found in Appendix I. This heuristic is based on the work of Leachman and Gascon.

The Importance of Stable Cycle Times

If capacity falls short to fill all forecast demand during the upcoming cycle, a VCT policy will decide to decrease the cycle time. Since the cycle time is inversely proportional to the total set-up time, the capacity spent on set-up will increase and the remaining capacity — to be used for production — will decrease. Thus, if there is no possibility to use extra capacity, the total output will decrease. This view leads to the following hypothesis: A VCT policy will lead to a reduction in service level at a higher level of utilization. We have done simulation experiments to test this hypothesis.

The main results are presented in Table I and can be summarized as follows (The detailed problem data and a description of the experiment are presented in Appendix I):

(1) The Variable Cycle Times heuristic performs well if the utilization rate ~~is not extremely high. Its performance however decreases if the utilization~~ rate increases. Cycle time is adjusted downward, if the target cycle time

Ratio of demand and net capacity	Minimum run length	Set-up as a percentage of capacity	Service level (percentage of demand filled)	Total cost (£)
0.750	1	42.3	62.8	110,297
0.750	24	26.7	96.4	80,229
0.958	1	36.6	58.5	96,392
0.958	24	14.1	80.6	50,617

Table I. Results of the Experiments with the Variable Cycle Times Heuristic is too long to avoid stockouts. As mentioned above, a downward adjustment of the operational cycle time leads to a loss of capacity. As extra capacity is not available (no overtime) and a lower demand level is not expected (very high level of average demand), this downward adjustment of the operational cycle time will lead to smaller batch quantities and less available capacity for production purposes.

(2) The performance of the Variable Cycle Times heuristic is strongly dependent on the minimum run length parameter (*m*), which has to assure that the cycle time does not become too short. This conclusion is an extension of the first one. The drop of the cycle time is limited by the minimum run length. A higher value of *m* will limit the fluctuations in the operational cycle time and keep the operational cycle time closer to the target cycle time. As the results show, a higher value of *m* considerably improves the performance of the heuristic in terms of fill rate

This leads to the following hypothesis: in the situation described above, control of production is only possible if the cycle time is controlled. If the cycle time is not kept stable, this will lead to a loss of capacity and a drop in system performance, in terms of fill rate.

Simulation results are available which show that fixed cycle times will lead to a higher service level than variable cycle times. These results were obtained by applying the elementary Fixed Cycle Times (FCT) heuristic as described in Appendix I. The results are presented in Table II.

Comparing the performance of the FCT with the performance of the VCT ($m = 24$), we see that the fill rate relatively increases by 3.1 per cent. However, total costs increase by 27 per cent. At the high demand level, the fill rate increases by 16.4 per cent while costs increase by 10.7 per cent only. So, especially at the high utilization level, we see that the FCT results in a better fill rate than the VCT.

As the fill rate increases, the contribution to the company profit resulting from sales will increase. Therefore, a trade-off will have to be made between the increase in cost and the increase in contribution. The predetermined cycle time determines to a great extent the service level and the costs involved. It is important therefore that this trade-off is made simultaneously with the determination of the cycle times.

To decide on this predetermined cycle time, therefore, it is necessary to decide beforehand how much of the (forecast) demand should be accepted. It is obvious that if more demand is accepted, more capacity will be needed for production and less will be available for setting up. Consequently, lot sizes and safety stocks will be larger and inventory costs will increase. Therefore, a trade-off should

Table II.
Results of the Experiments with the Fixed Times Heuristic

Ratio of demand and net capacity	Set-up as a percentage of capacity	Service level (percentage of demand filled)	Total cost (£)
0.750	25.0	100.0	101,562
0.958	10.1	93.8	56,035

be made between the extra contribution which may be realized by extra sales and the extra inventory holding costs which will be necessary to manufacture those products[8]. Based on this long-term decision, short-term actions should be evaluated in terms of this long-term objective in order to reach the level of sales decided upon. This can only be realized if the incoming orders are judged on both their contribution and cost consequences and on their capacity consequences. This is the central function of demand management in these situations, namely order acceptance in close co-operation with production control.

In the next section we will briefly describe a model which includes both the setting of the long-term parameters and the order acceptance and scheduling functions. A more detailed description can be found in Fransoo[9].

Short Description of the Model

A hierarchical model (see Bitran and Hax[10]) is proposed to control production in these kinds of situations. As mentioned previously, the central issue of the model is a customer order acceptance function, which accepts orders in such a way that production order scheduling on the most detailed level is relatively simple. A description of the aggregation-decomposition approach used here — in which solutions must be found not only in conceptual aggregation, but also in hierarchizing the decision process itself (decomposition) — can be found in Bertrand and Wijngaard[11] and in Bertrand *et al.*[12].

We will now consecutively discuss the three hierarchical levels of the model. The model is represented in Figure 1.

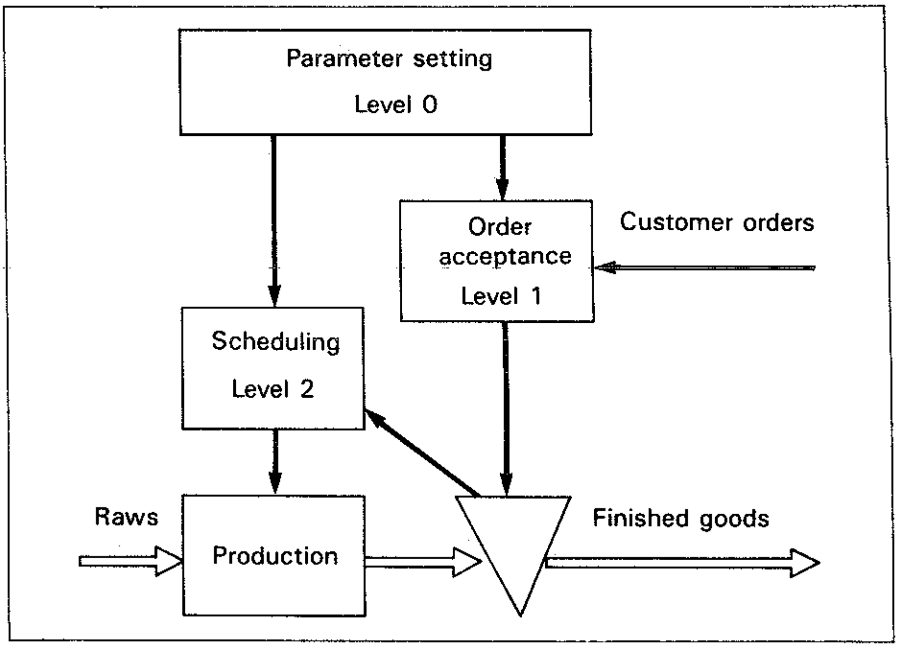

Figure 1. Three-tiered Hierarchical Model for Production Control in Process Industries

Level 0: Parameter Setting
The purpose of the top-level decision is to set the parameters according to which the customer order acceptance and production order scheduling functions will have to be executed. This decision should be taken periodically, e.g. once a year. At this level demand rates are assumed to be deterministic.

As stated before, a trade-off should be made between the extra contribution which may be realized by extra sales and the extra inventory holding cost. We will call the sales level that the company intends to accept the target sales level. Given a target sales level for each product and the available capacity, the cycle time for each product can be easily determined. At this level, the difference in contribution to the company profit of the various products plays an important role. The problem formulation is presented in Appendix II.

Level 1: Customer Order Acceptance
The purpose of the customer order acceptance function, which should be carried out continuously, is to accept orders in such a way that at least the target sales level can be met. On top of that, short-term opportunities which do not violate the system's long-term objectives should be taken as much as possible.

With regard to the kind of situations considered in this study, two types of flexibility can be distinguished:

- volume flexibility: the opportunity to enlarge the throughput
- mix flexibility: the opportunity to exchange committed capacity between different products.

As described above, capacity is fixed and cycle times should be kept stable. Therefore volume flexibility is not available at the customer order acceptance level. The demand manager can only use the available mix flexibility to react to short-term customer orders as well as he possibly can.

Level 2: Production Order Scheduling
If the order acceptance decision has been carried out well, it is fairly easy to compose a viable detailed production schedule. The order acceptance function will guarantee that, on an aggregate level, enough inventory will be available to assure that the cycle times can be maintained. A predetermined service level can be reached this way. The batch quantity will be the forecast demand during the cycle time, corrected for changes in accepted demand compared to the forecast demand.

Managerial and Organizational Implications

Although it may be clear that the proposed model works well from a production control point of view, its managerial and organizational consequences should not be underestimated. First of all, if the part of demand that can be accepted has been decided on, a decision should be made as to which customers will be served and which customers will not be served. This is a managerial decision. As these businesses are mostly working in an industrial market, this decision is a very important one and may have long-term consequences. The model offers decision-support information that may improve the quality of the decision. However, the model does not decide which customers are relatively more important than others.

Secondly, an important organizational feature of the model is that a common reference is presented for, on the one hand, the marketing and sales department and, on the other, the production department. In OR terms, this may all seem pretty obvious, but practice has shown otherwise. Though consequences of decisions may be clarified, personnel reward systems are still not based on integral objectives. According to Pritchard *et al.*[13] parts of the realization of the overall objectives should be taken into account for measuring the performance of each individual department.

Third, the behavioural aspect should be considered. The influence of individual customers orders on long-term objectives should not only be made clear, but also the present uncertainty about the future should be turned into a qualified risk.

Conclusions

The very high levels of utilization which are prevalent in process industries require a different production control system than under moderate capacity utilization levels. The production system we studied appears to be very sensitive to unbalanced short-term changes. Therefore, it is necessary to define — beforehand — which short-term changes will be allowed and which ones will not.

Here we have shown that short-term changes in the cycle time will lead to a lower service level in the long term. Therefore, we have developed a model which keeps these cycle times under control. An important characteristic of this model is the central position of the demand manager. The demand manager can influence the order stream and control the cycle times. A further analysis, both from a production control point of view (more exhaustive testing of the complete model) and from an organizational point of view (motivating strategies and organizational structures) is necessary.

Summarizing, we can say that production control and OR techniques can structure the order acceptance decision, but managers do have to take the consequences for wanting to realize a controlled production control system.

Notes and References

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8. Extra output over the long term is only possible if the productive capacity is increased and — as a consequence — the set-up capacity is decreased. To reach an increase in productive capacity, the cycle time will have to be increased. As a consequence, total inventory — which is dependent on cycle time — will rise.

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Appendix I. Experimental Setting

In this Appendix we will describe formally the two heuristics we tested in the experiments and describe the experimental design.

1. Notation

We use the same notation as Leachman and Gascon[6]:

i: Item index, $i = 1,\dots,n$. The item with the shortest run-out time will be indexed item 1.
t: Time period index.
c_i: Set-up time for product i, expressed in fractions of time periods.
P_i: Production rate of item i (units per time period).
I_i: Inventory level of item i at the start of the current period.
d_i: Forecast demand for item i for any period t.
σ_i: Standard deviation of demand (forecast error) for any period t.
ss_i: Safety stock level for item i.
m: Minimum production run time (hours)
RO_i: Expected run-out time for item i
T^*: Target fundamental cycle length
T_i^*: Target cycle time for item i ($T_i^* = k_i T^*$, k_i a positive integer).
T: Operational fundamental cycle length
T_i: Operational cycle time for item i ($T_i = k_i T$, k_i as before).
TS: Minimal total slack.

2. Variable Cycle Times Heuristic

The Variable Cycle Times (VCT) heuristic consists of the following steps:

(1) Calculate target cycle times, according to a procedure, based on the Doll and Whybark[7] procedure.

(2) Calculate run-out times and index them, so that $RO_1 < RO_2 < \dots < RO_n$:

$$RO_i = \frac{I_i - ss_i}{d_i}$$

(3) Calculate minimal total slack:

$$TS = \min_{i = 1,\dots,n} \left\{ RO_i - \sum_{j=1}^{i-1} \left(c_i - \frac{T_i^* d_i}{P_i} \right) \right\}$$

(4) If $TS<0$ then calculate operational cycle times:

$$T = \max\left(\frac{mP_1}{d_1k_1}, min\left(T^*, \min_{i=2,\ldots,n}\left(\frac{RO_i - \sum_{j=1}^{i-1} c_j}{\sum_{j=1}^{i-1} \frac{k_jd_j}{P_j}}\right)\right)\right)$$

(5) Take $int(TS)$ down periods, if $int(TS)>1$. Otherwise, produce item 1, in the quantity: $T_1d_1 - I_1 + ss_1$

(6) When a production run has been finished, or when the required number of down periods have passed, then continue in the next period with step 2

3. Elementary Fixed Cycle Times Heuristic

The elementary Fixed Cycle Times (FCT) heuristic consists of the following steps:

(1) Calculate target cycle times, based on Economic Manufacturing Quantity (EMQ).

(2) For this period, accept all orders, as long as the on-hand inventory is greater than or equal to the required quantity.

(3) If a production run finishes during this period, add the production run quantity to the on-hand inventory, and start producing the product with the shortest run-out time in a fixed quantity, which is based on the forecast demand during the target cycle time.

(4) Return to step 2 for the next period

4. Experimental Design

We considered five products with the following characteristics:

Product number	1	2	3	4	5
Arrival rate $1/\lambda$ (orders/period)	4	2	2	1	1

Orders were generated according to a Poisson process. The order size was set at 18 and 23, for the 75 per cent and 95.8 per cent demand/net capacity levels, respectively. The production rate was chosen at ten units per hour, or 240 units per time period (deterministic). Production was continuous (24 hours/day). Machines were 100 per cent available. Set-up time was chosen to be five hours, or 0.2085 periods, (deterministic), for all products.

Set-up costs were set at £150 per set-up, while inventory carrying costs were set at £0.05 per product per day, for all products. The safety stock was taken as (just as Leachman and Gascon did):

$$ss_i = 3\sigma_i\sqrt{c_i}\ , \text{ for all } i$$

Because we used a Poisson process, we defined:

$$\sigma_i = \mu_i\sqrt{\frac{1}{\lambda_i}}, \text{ where } \mu_i \text{ is the order size.}$$

All products of a production run only become available at the end of a run. We used a start run of 50 periods, and simulated consecutively for 350 periods. If sufficient stock was available, the order was filled, otherwise demand got lost; partial fulfilment was not possible. The service level was defined as the percentage of orders filled. The final service level for any situation was calculated as the average of three simulation runs of 350 periods each

Appendix II. Level 0 Problem Formulation

Maximize:

$$\sum_{i=1}^{n} ad_i b_i - \frac{s_i}{T_i^*} - (0.5\ T_i^*\ ad_i(1 - \frac{ad_i}{P_i}) + ss_i)h_i$$

Subject to:

$$\sum_{i=1}^{n} \frac{ad_i}{P_i} + \frac{c_i}{T_i^*} \leq C$$

$$d_i - \alpha_{1i}\ \sigma_i \leq ad_i \leq d_i + \alpha_{2i}\sigma_i$$

where

ad_i: Total demand to be accepted.

b_i: Net contribution of product i.

s_i: Set-up cost for product i.

h_i: Inventory holding cost for product i

C: Available net capacity.

d_i: Total forecast demand

σ_i: Standard deviation of demand.

α_{1i}, α_{2i}: Predefined minimum and maximum required service level for product i

P_i, T_i^*, ss_i, and c_i in Appendix I.