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A COMPARISON OF CAPACITY-ORIENTED AND PRODUCT-ORIENTED APPROACHES TO GOODSFLOW CONTROL

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ABSTRACT

An important type of production situations are the multi-product, multi-stage, make-to-stock situations. The main elements in such situations are products and resources. Coupled with these elements there are certain restrictions and objectives (capacity restrictions, objectives with respect to service performance, etc.). There are two extreme ways to structure the interference of these restrictions: the product-oriented approach and the capacity-oriented approach. These two approaches are described in this paper and for the one-stage case the performances of the approaches are analyzed and compared. The results suggest that in many situations it is possible to construct a simple combination of a capacity-oriented and a product-oriented approach which is close to optimal.

1. INTRODUCTION

An important type of production situations are the multi-product, multi-stage, make-to-stock situations. The main elements in such situations are products (in various stages of completion, including raw materials and components) and resources. Coupled with the final products there are restrictions and objectives with respect to the delivery patterns. These imply restrictions with respect to production patterns of intermediate products and with respect to the procurement of raw materials and components. Coupled with the resources there are restrictions with respect to production patterns of groups of products (capacity restrictions). The complexity of goodsflow control in such situations stems from the interference of both types of restrictions. In a way one may interprete the problem of designing a goodsflow control system as the problem of structuring this interference.

There are two important, extreme ways to structure this interference—the product-oriented and the capacity-oriented approach.

Product-oriented approach. First, required delivery patterns (Master Production Schedule) are formulated, ignoring any capacity restrictions. These delivery patterns are then translated into production patterns by offsetting, using standard throughput times. These production patterns are then coordinated, taking into account the capacity restrictions. Typically the horizon in this second stage is smaller than in the first. Uncertainties in required delivery patterns and capacity availability and the interference between products because of restricted capacities can be eased by safety stocks and safety lead time in the first planning step (per product). The MRP-I approach [1] and less extreme also the MRP-II approach are of this product-oriented type.

Capacity-oriented approach. First a capacity-use (aggregate production) plan is developed, possibly combined with a plan of when to increase and decrease the capacity. This requires aggregation of delivery patterns and inventories to capacities. Then, using short-term detailed information, the capacity use of the first period is allocated to the different products. This disaggregation can be based, for instance, on the run-out times of the individual products. Uncertainties in capacity availability and total required deliveries can be taken into account in the initial stage. Imbalances between the individual products resulting from this procedure may also be estimated in an aggregate way and hence it is possible to determine how much extra (aggregate) inventory is necessary because of these imbalances. Such capacity-oriented approaches have been proposed by Van Beek [2] and Meal [3]. Both assume that capacity use and capacity availability are equal.

Both approaches are feasible, but it is not clear when to use which approach. It may also be that both approaches work well in certain situations, while in other situations only a mixture of the approaches is satisfying. An interesting mixture of both approaches for the single-machine case is introduced by Graves [4]; he considers a specific single-capacity, multi-product model with periodic review, and proposes a so-called "composite-product" heuristic. Such a heuristic requires that in situations with N products, $2^N - N - 1$ single-capacity, single-product models be analyzed. This heuristic proved to perform better than the more product-oriented heuristics and suggests that a good heuristic has to contain capacity-oriented elements.

In this paper we will compare both approaches in their most extreme forms. The analysis is meant to show the fundamental differences between both approaches and to develop a generally applicable insight into their performance and methods to construct good combinations. The analysis is based on a simple model where both the capacity aspect and the product aspect play a role: a single-stage, multi-product, finite-capacity case. Since it is reasonable to expect that the level of short-term fluctuations and disturbances will play an important role in the comparison of both approaches, both the capacity availability and the capacity requirement are modelled to be stochastic.

The model is described in Section 2. Capacity-oriented and product-oriented strategies for this case will be described in Sections 3 and 4, respectively Numerical results for a specific choice of parameters will be given and discussed in Section 5. These results are extended in Section 6 to the model of Section 2. That model is specific with respect to the following points:

— identical products;
— fixed run size; and
— no predictability.

Possibilities to extend the results to more general single-stage systems are considered in Section 7. For a discussion on the multi-stage case we have to refer to Ref. [5].

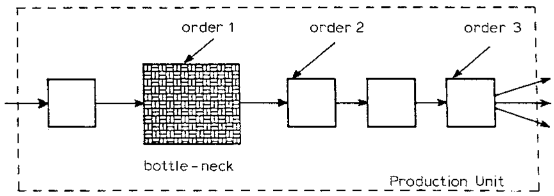

Fig. 2. A production unit with a single bottleneck.

2. A SINGLE-STAGE MODEL

In the system under consideration there are N products (see Fig. 1). A stationary Poisson process with parameter λ generates customer arrivals. Each customer orders with probability $1/N$ a certain amount S of product j. The demand size S is also stochastic.

A stationary stochastic process P generates production opportunities. At each production opportunity one may start a production run of size q for one product.

The produced batch will become available after a lead time l. This implies that there may be more production orders in process and makes it easier to apply the results in situations with more than one production stage but only one clear bottleneck (see Fig. 2). Backordering is allowed and therefore inventories may become negative. The performance criterion is the average value of

$$\sum_{j=1}^{N} p(I_j(t))$$

where $p(\cdot)$ is some convex penalty function.

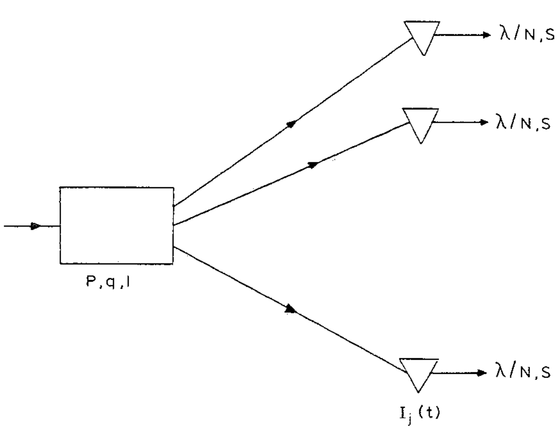

Fig. 1. A single-stage model.

At each production opportunity one has to decide whether or not to produce, and if so, which product should be made. Since the arrival process is Poisson it is sufficient to let this decision depend on the actual inventory positions (the amount on hand plus on order, minus backorders per product).

Capacity-oriented strategies are strategies in which the decision whether or not to use a production opportunity depends on the aggregate inventory position, i.e., the total amount on hand plus on order, summed over all products:

$$I_{\text{pos}} := \sum_{j=1}^{N} I_{\text{pos},j}$$

In this stationary case with a convex penalty function it is sufficient to consider strategies characterized by some critical number: produce (use production opportunity) if and only if

$$I_{\text{pos}} \leqslant I_0 \quad (\text{for some } I_0)$$

The second step in a capacity-oriented approach is the disaggregation step, i.e., the assignment of the production run. In this case of identical products and a convex penalty function it is optimal to assign the production run to the product with the smallest inventory position.

In the **product-oriented** approach the first step is to determine per product whether or not a production run is necessary. In this purely stochastic case with identical products the products are considered for a production run if the inventory position is less than or equal to some critical number I_0.

Coordination is necessary if there is more than one product being considered for a production run. Just as in the capacity-oriented approach it is optimal to assign the production run to the product with the smallest inventory position. Product-oriented strategies are of the following type: produce if and only if

$$\operatorname*{Min}_j \{ I_{\mathrm{pos},j} \} \leqslant I_0 \qquad (\text{for some } I_0)$$

and assign the production tun to the product with the smallest inventory position.

To compare both approaches the average cost with cost rate

$$\sum_{j=1}^{N} p(I_j(t))$$

is used as performance criterion.

In case of a positive lead time l the production decision at time 0 only influences the cost from time l on. Therefore the case of lead time l can be reduced to the case of leadtime 0 by using a different penalty function:

$$p^l(I_{\mathrm{pos},j}(t)) := \int_x p(I_{\mathrm{pos},j}(t) - x) \,\mathrm{d}G^{(l)}(x)$$

where $G^{(l)}(\cdot)$ is the distribution of the demand of product j during the lead time. The convexity of $p(\cdot)$ implies the convexity of $p^l(\cdot)$.

3. CAPACITY-ORIENTED STRATEGIES

The performance under some strategy π may be written as:

$$\int_{x_1,\ldots,x_N} \left\{ \sum_{j=1}^{N} p^l(x_j) \right\} \mathrm{d}F^{\pi}(x_1,\ldots,x_N)$$

where $F^{\pi}(x_1,\ldots,x_N)$ is the steady-state distribution of the inventories (or inventory positions) under application of strategy π. To analyse the quality of the capacity-oriented approach it is useful to write the performance in the following way:

$$\int_x g^{\pi}(x) \,\mathrm{d}F^{\pi}(\mathrm{x})$$

with $F^{\pi}(x)$ the steady-state distribution of the aggregate inventory position and

$$g^{\pi}(x) := \int_{x_1,\ldots,x_N} \sum_{j=1}^{N} p^l(x_j) \times \mathrm{d}F_{\mathrm{c}}^{\pi}\left(x_1,\ldots,x_N \,\middle|\, \sum_{j=1}^{N} x_j = x \right)$$

with

$$F_{\mathrm{c}}^{\pi}\left(x_1,\ldots,x_N \,\middle|\, \sum_{j=1}^{N} x_j = x \right)$$

the steady-state conditional distribution of the individual inventory positions, given the aggregate inventory position.

Having chosen a capacity-oriented approach, the next problem is to determine the optimal capacity-oriented strategy. Unfortunately this is almost as complex as the problem to determine the overall optimal strategy, because the determination of $g^{\pi}(\cdot)$ is an N-dimensional problem. The optimal capacity-oriented strategy is interesting as point of reference, but not useful in practice. It is important therefore to consider capacity-oriented strategies based on simple approximations of $g^{\pi}(\cdot)$.

The most trivial approximation is

$$g^1(x) = Np^l(x/N)$$

Such an approximation is based on the assumption that the inventory positions of all products can be kept equal to each other. The strategy resulting from this approximation, i.e., minimizing

$$\int_x g^1(x) \,\mathrm{d}F^{\pi}(x)$$

over all capacity-oriented strategies, is called the simple capacity-oriented heuristic (SCH). The determination of the performance of this heuristic is an N-dimensional problem and hence simulation was used to evaluate the heuristic, the results of which are presented in Section 5.

The convexity of $p^l(\cdot)$ implies $g^1(x) \leqslant g^\pi(x)$, which means that the minimum of

$$\int_x g^1(x)\,\mathrm{d}F^\pi(x)$$

is a lower bound for the optimal average cost (OC). This lower bound is called the capacity lower bound (CL). So we have the inequality CL $\leqslant$ OC $\leqslant$ SCH. The results in the next section show that in many cases CL and SCH are very close and therefore also very close to the optimal average cost.

It is possible to construct more advanced heuristics to approximate $g^\pi(\cdot)$ taking into account that the inventory positions of the individual products cannot be kept equal. For instance in case of large batch sizes it will not be possible to keep the inventory positions equal and in such cases one may assume that the inventory positions of the individual products fluctuate randomly around x/N where x is the aggregate inventory position. Bemelmans [6] used the following approximation:

$$g^2(x) = \frac{1}{q+1} \sum_{j=x/N-q/2}^{x/N+q/2} p^l(y)$$

This approximation turned out to work better indeed than the approximation $g^1(\cdot)$ for cases with large batch sizes.

4. PRODUCT-ORIENTED STRATEGIES

In the product-oriented approach a certain product will demand the use of a production opportunity if its inventory position is less than or equal to some critical value I_0. The problem is to determine this I_0. Unfortunately this is again an N-dimensional problem. The possible delay because of other, more urgent products which also demand a production run has to be taken into account. The difficulty is that subsequent delays are not independent of each other and not independent of the inventories.

As in the capacity-oriented approach it is important to consider heuristics. The most trivial heuristic is that where the critical value I_0 is based on the assumption that the products do not interfere at all. The resulting strategy is called the simple product-oriented heuristic. The critical level in this heuristic can be determined from a one-product model assuming that all production opportunities are available for that product (see Ref. [6]). However, to determine the performance of this heuristic (SPH) is again an N-dimensional problem, whose simulation results are given in the next section.

Let M be the minimal cost in the one-product model. Then NM is a lower bound for the overall optimal cost (OC) because no interference is assumed. This lower bound is called the product lower bound. We have the inequality $NM \leqslant$ OC $\leqslant$ SPH. Combining this with the corresponding inequality from the capacity-oriented approach gives

$$\mathrm{Max}\{NM,\mathrm{CL}\} \leqslant \mathrm{OC} \leqslant \mathrm{Min}\{\mathrm{SPH},\mathrm{SCH}\}$$

This inequality will be used in Section 5 to interprete the results. It is possible to construct a better product-oriented heuristic by modelling the delays as independent samples from the steady-state waiting time [7]. Whether it is useful to apply such more advanced heuristics will depend on the difference

$$\mathrm{Min}(\mathrm{SPH},\mathrm{SCH}) - \mathrm{Max}(NM,\mathrm{CL}).$$

5. NUMERICAL RESULTS

In this section numerical results will be given for the case where:

- inventory holding cost and stock-out cost are linear, i.e., $p(I_j) = aI_j^+ + bI_j^-$ where $I^+ = \max(0, I)$ and $I^- = \max(0, -I)$;
- the demand size equals one at each demand instant; and
- production opportunities are generated by a Poisson process with parameter $\mu = 1$.

It should be noticed that this is only a special case of the model discussed in Section 2. To which extent the results are influenced by this, will discussed in Section 6.

The results for both the capacity- and the product-oriented heuristic, for this specific case, are given in Table 1. The first row in Table 1 shows the results for the case $a = 1$, $b = 3$, $\lambda = 1.67$, $N = 2$, $q = 2$, $l = 0$, which leads to a utilization rate of $\rho = 1.67/2 = 0.835$. In each of the other rows one of the parameters has been changed, except in row 8 where both q and λ have been changed to the same utilization rate as in row 1.

The results show that the simple capacity-oriented heuristic performs better than the simple product-oriented heuristic, except in the case with a very low utilization rate ($\lambda = 0.5$) and the case with many products ($N = 20$). This can be expected, since in case of a limited, stochastically available capacity, the queueing phenomenon will lead to large delay times. In such a case, the capacity-oriented heuristic, which explicitly takes into account the effects of a finite capacity, performs best. Consequently, it may be expected that when the utilization rate is low, or when the capacity availability is less stochastic, the simple product-oriented heuristic performs better. We will return to this hypothesis in Section 6, where we consider several other capacity-availability processes.

TABLE 1

Results for the simple heuristics for negative-exponentially distributed interarrival times between production opportunities

	CL	NM	SCH	SPH
(1) Reference case	11.42	4.58	11.79	17.43
(2) $\lambda = 0.5$, $\rho = 0.25$	1.50	1.74	2.37	1.87
(3) $\lambda = 1.8$, $\rho = 0.9$	19.63	5.08	20.02	30.31
(4) $N = 5$	11.42	5.24	12.88	19.80
(5) $N = 20$	11.42	11.94	21.83	21.37
(6) $b = 1$	5.71	2.28	5.84	7.20
(7) $b = 10$	19.75	7.82	19.80	36.10
(8) $\lambda = 8.35$, $q = 10$	41.35	16.56	42.08	60.08
(9) $l = 5$	11.95	7.08	12.69	17.21
(10) $l = 10$	12.47	8.79	13.90	16.80

That the simple product-oriented heuristic gives better results for $N = 20$ seems reasonable: while the aggregate inventory position tends to be a worse measure for the state of the system, it becomes less harmful to model the products individually in case of many products. This second effect can be explained as follows: the delay due to other products depends (mainly) on the utilization rate, which stays constant if the number of products increases. The average demand per product decreases. Therefore the demand per product during the period it queues for allocation of the capacity decreases.

When l increases, the simple product-oriented heuristic gets better. To understand this, it has to be realised that a change in l will have similar effects as a change in $p^l(I_{\text{pos}})$ (see the definition of $p^l(\cdot)$). Figure 3 shows a comparison of $p^l(I_{\text{pos}})$ for $l = 10$ and $l = 0$. In the case of $l = 10$, the minimum of $p^l(I_{\text{pos}})$ is higher and the slopes are less steep. Consequently, the influence of a delayed production due to other products is smaller in the case of $l = 10$ than in the case of $l = 0$.

From Table 1, we also see that max(CL, NM) = CL, except in the cases where $\lambda = 0.5$ and $N = 20$. These are also the only cases where SPH < SCH. This suggests an operational criterion for choosing between the simple capacity-oriented heuristic and the simple product-oriented heuristic.

This criterion can be explained (see Fig. 4): since both lower bounds, NM and CL, are

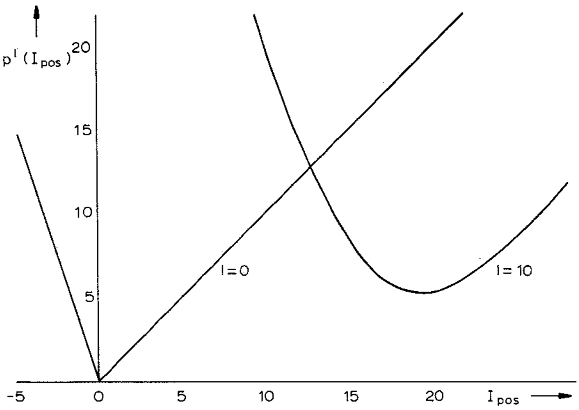

Fig. 3. Comparison of $p^l(I_{pos})$ for $l=0$ and $l=10$; $a=1$, $b=3$.

less than the cost of the overall optimal strategy (OC), it is obvious that the maximum of both is nearest to OC. If one lower bound is nearest to the actual cost, it may be argued that the assumptions that led to this lower bound are more realistic and therefore the corresponding heuristic will perform best. At this point, the criterion may seem somewhat speculative, but we will verify it in Section 6.

Only for $N=5$, $N=20$, $l=5$ or $l=10$, the difference between the highest lower bound and its corresponding heuristic is significant. Since the cost of the overall optimal strategy always lies between max(NM,CL) and min (SPH,SCH) (see Fig. 4), the heuristic corresponding to the highest lower bound is almost optimal in all other cases. To investigate whether these differences are due to poor approximations of the aggregate cost and the production delay, the optimal capacity-oriented and product-oriented strategies have been determined by means of simulation. In Table 2 these results are denoted for the situations of interest. The structure of the table is as in Table 1.

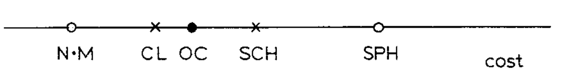

Fig. 4. Relation between the costs.

TABLE 2

Results for the optimal capacity-oriented and product-oriented strategies for negative-exponentially distributed interarrival times between production opportunities

	Capacity-oriented strategy	Product-oriented strategy
(4) $N=5$	12.75	12.65
(5) $N=20$	20.68	21.37
(4) $l=5$	12.69	12.81
(10) $l=10$	13.44	13.70

It turns out that there is little improvement when using the optimal capacity-oriented or the optimal product-oriented strategy instead of the best of the two simple heuristics. Therefore, in the situations considered here, there is no need to use more advanced heuristics. In cases where N and ρ are both large it may be useful to use more advanced heuristics [6].

6. SENSITIVITY OF THE RESULTS

In Sections 2 to 4, we discussed a relatively general single-stage multi-product problem, and we have put forward capacity-oriented and product-oriented strategies and heuristics. These strategies and heuristics have been evaluated in the previous section. This evaluation, however, was based on the analysis of a specific version of the model. The main conclusions of this evaluation were:

(1) The best of the two simple heuristics is close to optimal.

(2) It is best to choose the simple capacity-oriented heuristic when the corresponding lower bound is highest (CL > NM) and the simple product-oriented heuristic otherwise.

In this section, we want to investigate whether these results can be extended to the general model of Section 2 or whether they result from the choice of the specific model of Section 5.

Since the model of Section 5 is specific in three respects, the sensitivity analysis in this section will consist of three elements as well:

— sensitivity for the cost rate $p(I_j)$;
— sensitivity for the process that generates production opportunities; and
— sensitivity for the distribution of the demand-size (S).

6.1 Sensitivity for the cost rate $p(I_j)$

For any given convex cost rate $p(I_j)$, with $p(I_j \to \infty$ for $j \to \pm\infty$, the same approach can be used in order to find the heuristics and their corresponding lower bounds. As illustrated in Fig. 3, the performance of the strategy depends on the height of the minimum of $p(I_j)$ (or equivalently $p^l(I_{\text{pos},j})$ when $l > 0$) and on the steepness of the slopes near the minimum.

Therefore the sensitivity for $p(I_j)$ has been checked sufficiently by comparing the case where $b = 3$ and $l = 0$ with the cases where $b = 1$, $h = 10$, $l = 5$ or $l = 10$. Consequently, one may expect to find a strategy that is almost optimal in situations with other cost rates as well, if one chooses the simple heuristic indicated by the criterion derived in Section 5.

6.2 Sensitivity for the process that generates production opportunities

To understand better the sensitivity of the results for the process by which capacity becomes available, the heuristics have been applied to systems with different distribution functions of the time between successive production opportunities, namely

$$C_2(x) = 1 - e^{-2x}(1 + 2x)$$

and

$$C_3(x) = 1 - 0.7887e^{-1.5774x} - 0.2113e^{-0.4226x}$$

It is easy to check that both distributions have the same mean ($= 1$) as the distribution that is used in Section 5, whereas the variance for $C_2(x)$ is 0.5 and the variance for $C_3(x)$ is 2.

It turned out that the criterion to use the simple heuristic for which the corresponding lower bound is maximal, again chooses the best heuristic in each situation and that, just as in the case considered in Section 5, the best heuristic was close to optimal. This suggests that the conclusions are indeed insensitive for the production opportunity process.

The results for $C_2(\cdot)$ and $C_3(\cdot)$ make it also possible to check the influence of a change of the second moment of the distribution of the time between subsequent production opportunities on the choice between the capacity-oriented and the product-oriented approach. The results indeed confirmed the conjecture that a higher variance makes it more attractive to use a capacity-oriented approach.

6.3 Sensitivity for the distribution of the demand size (S)

For the specific model in Section 5, we assumed that the demand size S equals 1. To check whether the assertions for the specific model depend on this assumption, consideration is given to a model with compound Poisson demand. The only difference from the model of Section 5 is that S is stochastic now. We have chosen the following distribution for S (notice that $E(S) = 1$).

$$S = \begin{cases} 0 \text{ with probability } 2/3 \\ 3 \text{ with probability } 1/3 \end{cases}$$

From the results for this model it could be seen that, again, the simple capacity-oriented heuristic performs best when $\text{CL} > NM$ and also that the performance of the best heuristic is close to optimal.

7. EXTENSIONS AND REMARKS

In this paper, we compared the capacity-oriented and the product-oriented approaches for a single-stage model with identical products in which demand is purely stochastic.

It has been proved that simple heuristics, based on the capacity-oriented approach or on the product-oriented approach perform well in such models. This analysis also led to approximations of the costs of these heuristics. Using these approximations, a criterion has been found to choose between the capacity-oriented and the product-oriented approaches. According to this criterion, the heuristic is chosen for which the approximation of the cost is maximal.

The heuristic that is indicated by this criterion performs well in the situations that have been investigated in this paper. As might be expected, the capacity-oriented approach performs best in cases of a tight capacity-restriction, whereas the product-oriented approach becomes better as the number of products increases. The variance of the availability of the capacity plays also a role in the choice between the capacity-oriented and the product-oriented approaches. In case of a high variance, the capacity-oriented approach is more attractive.

In Section 6 a sensitivity analysis is given for the parameters of the general model with identical products and a purely stochastic demand. As mentioned already in Section 2 the main restrictive characteristics of the single-stage model considered here are

— identical products,
— no predictability,
— fixed run sizes.

We will give attention to each of these points.

Possibilities to apply the same approach to multi-stage models are sketched in Ref. [5].

7.1 Identical products

The results suggest that neither the simple capacity-oriented heuristic nor the simple product-oriented heuristic works well in cases of many products and a high utilization rate. In such situations one might use the more advanced capacity-oriented and product-oriented heuristics described in Sections 3 and 4. In cases of many products the demand rate generally varies widely over the products. This does not severely affect the (advanced) product-oriented heuristics because these are essentially based on one-product analyses [7], but it does affect the capacity-oriented heuristics because these are based on aggregation and aggregation gets more difficult for very different products. However, the quality of the (advanced) product-oriented heuristics depends heavily on the stationarity of the situation. The capacity-oriented heuristics are easier to transfer to non-stationary systems.

To adapt the capacity-oriented heuristics to the case with many products one may distinguish a group of fast movers and a group of slow movers. The slow movers are given priority [6]. That means that the capacity restriction is not tight for the slow movers. The slow movers can be controlled by a product-oriented strategy. The capacity that is left for the fast movers is tight. The fast movers can be controlled by a capacity-oriented strategy.

7.2 No predictability

In case of identical products and no predictability it is optimal to assign a production run to the product with the smallest inventory position. In case of predictability this is not necessarily so. Predictability generates short-term differences between the products. Assignment based on the inventory position (myopic assignment) is suboptimal in this case. Bemelmans [6] has shown, however, that for a wide range of situations myopic assignment is close to optimal. Within the class of strategies with myopic assignment one can distinguish again capacity-oriented strategies and product-oriented strategies. The results of the stochastic case can be extended to the partly predictable case with myopic assignment. In case of non-identical products the assignment can be based on the run-out times instead of the inventory positions. Although this is not optimal [8], one may expect to get good heuristics in this way.

7.3 Fixed run sizes

Fixed run sizes are chosen because in our opinion run sizes and utilization rate interfere heavily in general. This can be due to set-up times or to the influence on the possibility of an efficient usage of capacities [9,10]. The results of Graves [4] suggest that adaptable run sizes can improve the performance of the control as long as there is no effect on the utilization rate. When the run sizes interfere with the capacity one possibility is to fix only the average run size and to keep the run sizes free within that restriction. Such a decision freedom can be used in the determination of the production run. It will improve both extreme approaches (capacity-oriented and product-oriented). Since this possibility will lead to more equal inventory positions one may expect that the simple capacity-oriented heuristic gains more than the simple product-oriented heuristic. However, further research is necessary.

The assumption of fixed run sizes or at least fixed average run sizes leads to the simple cost structure of the models considered. Once the (average) run sizes are determined, production control is only a matter of timing. The objective of this timing is to follow the demand as close as possible. The degree to which the demand is followed can be measured by inventory cost and stock-out cost. Total set-up time and set-up cost is already determined at a higher level of control where the (average) run sizes are determined.

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