An Improved Heuristic for Long-term Planning in a Hierarchical Model with Cyclical Schedules

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1. Introduction

In this paper we will study a single machine multiple product production system. We will especially focus on the production control function in such a system. The system is characterized by the following special characteristics:

- high change-over times (independent of sequence)
- high utilization of capacity (all capacity is used either for production or for change-overs)
- demand is stationary and stochastic
- backordering is not allowed; if any order cannot be delivered out of stock, demand gets lost
- differences between the products in terms of contribution margin, inventory cost, and set-up cost

The practical relevance of studying such a system has originated from flow process industries, such as bulk chemicals, glass manufacturing, paper production and steel molding. The production control problem that is encountered in many of these industries is to increase the service levels in the short run, without infringing on long-term commitments. These industries usually operate round-the-clock, and they are characterized by an extremely high utilization of capacity and virtually no volume flexibility.

We will choose a hierarchical approach to design a control structure for this production system. A hierarchical approach is chosen fro two reasons. First, in line with Meal (1984), we argue that the production control system should fit the organizational structure. It is clear that different organizational levels decide on long-term and short-term issues. This should be reflected in the decision structure. Second, there is a difference in modelling at each of the decision levels. At the long-term level, a profit maximization function may be formulated to set the logistics parameters, the central parameters which influence the characteristic behavior of the production control system. Below, we will see that there are two logistics parameters in this production control system, namely target cycle time and target inventory level. We will demonstrate that the setting of these parameters determines the performance of the production control system. Because of this, profit maximization is not necessary at the short-term level, but production control is the dominant issue. Therefore, at the short-term (operational) level procedures should be developed that realize – under dynamic conditions – the targets set at the long-term (tactical) level. This is the hierarchical relation between the two decision levels and involves the *internal validity* of the model. This differs from the hierarchical approaches known in the literature, such as the well-known approach developed at the Massachusetts Institute of Technology (Bitran and Hax 1977). The MIT-approach optimizes at each hierarchical level, whereas in our approach there will not be another optimization at the operational decision level (see Fransoo 1993 for a more detailed discussion regarding this issue).

In this paper, we will first briefly describe the logistics parameters. Logistics parameters are the central parameters which determine the behavior of the production system. After this description, we will focus on the long-term capacity coordination function. The function will be dealt with in three steps. First, in section 3, we will describe the function in general terms. Then, in section 4, we will describe the function as a nonlinear mathematical programming problem. In section 5, we will present a heuristic to solve the long-term capacity coordination

problem.
After the description of the tactical decision function, the results of a series of simulation experiments will be presented. We will complete this paper by discussing some conclusions.

2. Logistics parameters

We assume that the objective of a business is to maximize its profit in the long run. It may be less clear that, in the production system considered in this study, the maximization of the business's profit in the short run may not automatically lead to profit maximization in the long run. The principal parameter in this mechanism is the *cycle time*. The cycle time is the period of time between two consecutive starts of production runs of the same product on the single machine considered. The cycle time is the principal parameter to determine the profit in the manufacturing stage of a business. This influence on the profit is three-fold:

- Determination of total available productive capacity
- Determination of set-up cost
- Determination of inventory holding cost

The productive capacity is defined as the number of hours available for production within a certain period of time. If the cycle time increases, the productive capacity increases as well, since less capacity is then spent on setting up. If the cycle time decreases, the productive capacity will decrease since more capacity will be spent on setting up. If more set-ups occur, then the set-up costs will increase. Finally, the cycle time determines the inventory holding cost. If the cycle times are longer, it lasts longer before a product is manufactured again. Therefore, the batch quantity has to be increased, which causes the inventory cost to rise.

It is clear that the cycle time must concur with the capacity restrictions. Together, the productive capacity and the set-up capacity cannot exceed the available capacity. This balance should be kept at all times, especially if we keep in mind that the utilization rate may be very high. In order to realize the long-term objective, the cycle time cannot be reduced in the short run. A possible reason for short-term reduction of the cycle time might be the delivery of some extra products to a customer, while not reducing the quantities planned to deliver to other customers. If this is done, short-term interests (flexibility) are preferred to long-term interests (total throughput and profit). It is our hypothesis that *the basic principle for production control in the production system considered is to keep cycle times stable*. This hypothesis has been tested in Fransoo (1992).

The second parameter to be decided upon at the tactical decision level is the *target inventory level*. The target inventory level is the order-up-to level which determines the operational batch sizes. If the target inventory level is increased, the service level of that product will increase. Determining the target inventory levels for each of the products includes making a trade-off between the products. Due to the high levels of utilization it may not be possible to aim at a high service level for all products. Additionally, it may generate less profit if high service levels are targeted for all products. Due to the differences in contribution margin and cost structure, it may be desirable for some products to have less inventory, since the possible extra contribution raised with higher inventory levels, may be less.

If these parameters are set at the tactical decision level, the performance of the system at the operational level is more or less determined.

3. Description of the long-term capacity coordination function

The long-term capacity coordination decision is a decision in which many aspects of the organization are involved. It does not only consider the coordination between the marketing

and manufacturing departments, but also the consequences which this long-term decision has upon the operational execution of day-to-day tasks (coordination of long-term and short-term effects. Coordination models have been developed and published in the literature (e.g. Damon and Schramm (1972), Freeland (1980), Abad and Sweeney (1982)). However, the operational consequences of these aggregate models have not been investigated. Additionally, these models only consider a single pseudo-product, and therefore are unable to distinguish between the various products. In our research, we explicitly deal with differences between the products. Therefore, we have to develop a new model.

The long-term capacity coordination decision is a decision at the tactical level of the organization. This means that the strategic decisions already have been taken. Among others, this includes the procurement of the resources (what is the available capacity?) and the determination of the product mix (which are the products that will be produced?). Consequently, at the tactical level a decision has to be taken how the available capacity will be used. Above, we have demonstrated the importance of stable cycle times for this kind of situation. Any decision about a more or less fixed cycle time requires a decision about the allocation of capacity. This allocation decision has two aspects:

1. The distribution of capacity over productive capacity and set-up capacity. Productive capacity is the capacity used for production; set-up capacity is the capacity used for changing over and setting up.
2. The distribution of productive capacity over the product range.

The distribution over productive and set-up capacity should be determined by the product contribution margin, the set-up cost and the inventory holding cost of a product. More productive capacity can only be created if the amount of set-up capacity is reduced. This will result in less set-up cost, but in increased inventory holding cost. These two costs are considered in the classical Economic Manufacturing Quantity formula. An important effect of the increase of the amount of productive capacity – which is *not* considered in the classical EMQ that is intended for uncapacitated situations – is that more units can be produced, so that the gross contribution will be increased. In EMQ-based approaches of the ELSP, a larger demand rate leads to a smaller cycle time. In Doll and Whybark (1973)'s approach, for instance, the cycle time is inversely proportional to the square root of the demand rate. Consequently, an increase in demand will not lead to an increase in cycle time, but to a decrease. It can be shown that this is true for all situations in which a single product does not consume more then half of the total production capacity. The Doll and Whybark procedure has been developed for low demand situations. In this paper we extend their approach to account for the high demand situations. This results in a capacitated problem formulation.
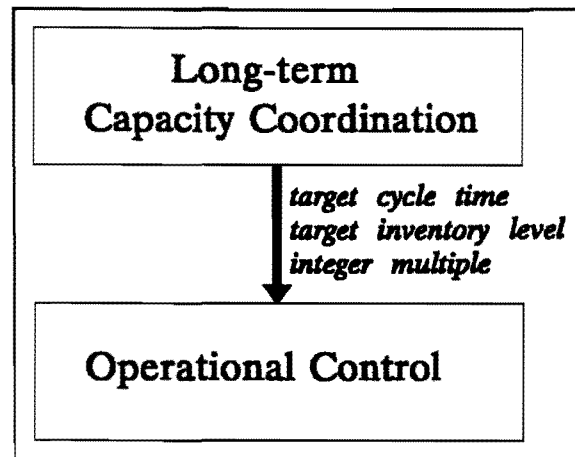
3

Figure 1   *Two-tiered control model*

Figure 1 presents the control hierarchy. We assume that the objective of the long-term capacity coordination problem is to maximize the expected profit. The height of the profit is determined by both aspects of the allocation decision. We will see that both aspects are included in the mathematical formulation of the problem. The expected contribution is determined by the expected gross contribution, set-up cost, and inventory holding cost. The maximization of the expected profit under the given capacity and service level restrictions results in the setting of the control parameters. These parameters are used at the operational level to decide on the short-term schedule.

The service level that will be reached is determined by the *target inventory levels* of each product i (I_i^*). The target inventory level is the order-up-to level which determines the operational batch sizes. The *cycle time of product* i is the time between two consecutive runs of product i. The *target cycle time of product* i (T_i^*) is the cycle time which results if at each production run the selected product is produced up to its target inventory level. For each product, the target cycle time is a function of the target inventory level. Moreover, each product should be produced according to an integer multiple of a basic cycle (analogous to the approach by Doll and Whybark). The control parameters to be decided upon at the tactical decision level then are, for each product, the target inventory level I_i^* and the integer multiple k_i. Note that order acceptance is not a separate decision function in the control hierarchy. This is caused by the fact that any customer orders which cannot be delivered directly out of stock, get lost (*"lost sales"*).

We will assume that at the operational level, the products will be manufactured in a fixed sequence. Each time a production run is finished, the batch size of the next product to be produced is determined. The batch size equals the target inventory level minus the actual inventory level. The product is then set up and the production run is started.
The formulation of the long-term capacity coordination problem in this section will assume that the scheduling decisions at the operational level are taken in this way.

The selection of the level of I_i^* has direct consequences for the service level and the expected inventory pattern. This depends on the ratio between I_i^* and $d_i T_i^*$ (d_i is the *average demand rate*, i.e. the average level of demand for product i per period).

4. Mathematical formulation of the capacity coordination problem
In this section, the problem will be formulated as a nonlinear programming problem. The

4

mathematical description of the problem is essentially the same as the qualitative description in the previous section. The decision structure in which the long-term capacity coordination problem is formulated, is the same as indicated in the previous section.

As indicated above, the control parameters are, for each product i, the target inventory level (I_i^*) and the integer multiples k_i. The resulting (target) cycle time is the result of these two parameters. This relation is expressed in equation 1.

$$T_i^* = k_i \sum_{j=1}^{n} \left\{ \frac{1}{k_j p_j} \left[I_j^* - \sigma_j \sqrt{T_j^*} \; E \left[\frac{d_j T_j^* - I_j^*}{\sigma_j \sqrt{T_j^*}} \right] \right] + \frac{c_j}{k_j} \right\} \quad (1)$$

where

	d_i	=	average demand for product i per period
	σ_i	=	standard deviation of demand for product i per period
	c_i	=	set-up time for product i (periods per set-up)
	p_i	=	production rate of product i (units per period)
	$E(.)$	=	partial expectation function according to Brown (1963)

The target cycle time T_i^* is an integer multiple (k_i) of a basic cycle time T^*. The target cycle time is comprised of the production runs of each product (rationed according to the respective k_i's) and the set-up time of each product (rationed in the same way). The length of the production run is determined by the difference between target inventory level and actual inventory level at the start of a new production run. The expected inventory level at the start of a new production run is a function of the target inventory level, the target cycle time and the demand rate of a product. This function is based on the partial expectation function (Brown 1963, 371). Note that equation 1 controls the allocation of capacity. The selection of the target cycle times ensures that the required service levels can be met.

Given the target inventory levels, the expected service levels can be determined. Again, the service level is defined as the *fill rate*, i.e. the portion of demand that is filled out of stock. Note that any demand that is not filled out of stock gets lost (no backordering). We define the *expected fill rate* of a product i as the fill rate that is expected for product i, given the characteristics of demand (mean and variance), the target cycle times, and the target inventory levels. An expression for the expected fill rate (EFR_i) is presented in equation 2.

$$EFR_i = \frac{d_i T_i^* - \sigma_i \sqrt{T_i^*} \; E \left[\frac{I_i^* - d_i \sqrt{T_i^*}}{\sigma_i \sqrt{T_i^*}} \right]}{d_i T_i^*} = 1 - \frac{\sigma_i}{d_i \sqrt{T_i^*}} E \left[\frac{I_i^* - d_i T_i^*}{\sigma_i \sqrt{T_i^*}} \right] \quad (2)$$

Equation 2 shows that the expected fill rate is computed by deducting the portion of demand that will not be delivered (on average) from 1. If we know the expected fill rate, the target inventory level, and the target cycle time, we can determine the expected profit per period. The expected profit consists of the expected contribution, the expected inventory holding cost, and the expected set-up cost. These are represented in equation 3.

$$\sum_{i=1}^{n} \left\{ b_i d_i EFR_i - \frac{1}{2} \left[I_i^* \left[1 - \frac{d_i}{p_i} \right] + \sigma_i \sqrt{T_i^*} \, E \left[\frac{d_i T_i^* - I_i^*}{\sigma_i \sqrt{T_i^*}} \right] \right] h_i - \frac{u_i}{T_i^*} \right\} \tag{3}$$

where b_i =   contribution margin per unit of i

                u_i =   set-up cost

It is obvious that the portion of demand that is expected to be filled determines the contribution (first term of the equation). We estimate the average inventory as the mean of the highest and the lowest expected inventory positions. The highest inventory position is the target inventory level, reduced by the demand during production. The lowest inventory position is the inventory level at the end of the cycle. Finally, the set-up costs are directly related to the target cycle time (which is proportional to the reciproke of the set-up frequency).

The set of equations mentioned above describes the operational behavior of the system in aggregate terms. The parameters to be influenced at this level are the target inventory level I_i^* and the integer multiples k_i. If these are set, then the target cycle time is determined according to equation 1. Maximization of equation 3 as a function of I_i^* and k_i^* (replace T_i^* in equation 3 by equation 1, and EFR_i in equation 3 by equation 2) should result in the approximate optimal setting of the parameters. Obviously, the objective function is very complex. The function is non-linear in its decision variables I_i^* and k_i, and also the interaction between each of the product cycle times and inventory levels is very complex.

The objective function is subject to a service level constraint. It is important that some management-specified minimum service level is guaranteed for each product. This decision should be taken at the strategic decision level and should be a constraint for the tactical decision described in this chapter. A minimum service level is realistic from a business point of view. If it did not exist, it might be possible that for some product(s) – especially those with a small contribution margin – no demand will be accepted during the year. In that case, it is unlikely that the product would be part of the product mix of this business. In order to obtain a feasible production schedule, it is necessary that the minimum service level can be met within the capacity constraints. On the other hand, a maximum service level is necessary to account for realistic planning. These service level constraints are represented in equation 4.

$$\alpha_{1i} \leq EFR_i \leq \alpha_{2i} \tag{4}$$

where α_{1i} =   predefined minimum service level for product i.

                α_{2i} =   predefined maximum service level for product i.

The problem of maximizing (3) subject to (4) will be called the capacity coordination problem. The capacity coordination problem is aimed at the determination of the cycle times and the distribution of the available capacity over the product range. The model considers the cost structure of the different products, the capacity they consume, and the demand distribution of each of the products. The model also takes into account the differences in service levels due to the fact of some I_i^*s being larger than some $d_i T_i^*$s. Of course, other operational procedures can be implemented than the ones assumed in this aggregate model. The objective of this

paper, however, is to present the long-term model to find a solution. It is clear that the problem is nonlinear in k_i and I_i^*. Due to this complexity we propose a heuristic for determining the two decision parameters. This heuristic should not only provide us with a good parameter setting, but should also be easily transferable to a practical decision structure.

5. The Capacity Coordination Heuristic

A rough analysis of the objective function tells us that the function has a maximum. At some combination of target inventory levels, an increase in inventory would lead to an increase in holding costs which exceeds the increase in expected contribution. At the same combination of inventory levels, a reduction in inventory would lead to a reduction in inventory holding cost which is less than the reduction in expected contribution. The function value around the maximum, however, is expected to be rather flat, since many combinations of the individual target inventory levels may generate about the same result.

Given the target inventory levels and the values of each k_i, the value of the objective function can be found. The integer multiples can be found while minimizing the cost given a certain fill rate. Using these two observations, a heuristic has been constructed. This heuristic is presented below.

Step 1. For all i: $k_i := 1$

Step 2. For all i: Set I_i^*, so that $EFR_i = \alpha_{1i}$

Step 3. Based on the actual value of I_i^*, compute T_i^*, for all i, according to:

$$T_i^* = k_i \sum_{j=1}^{n} \left\{ \frac{1}{k_j p_j} \left[I_j^* - \sigma_j \sqrt{T_j^*} \, E\left[\frac{d_j T_j^* - I_j^*}{\sigma_j \sqrt{T_j^*}} \right] \right] + \frac{c_j}{k_j} \right\}$$

Step 4. Determine the integer multiples according to the procedure presented in Exhibit 4.5.

Step 5. If any of the multiples have been changed in Step 4, then adjust I_i^*, for all i, so that all EFR_i remain unchanged.

Step 6. Calculate the expected profit according to:

$$\sum_{i=1}^{n} \left\{ b_i d_i EFR_i - \frac{1}{2} \left\{ I_i^* \left[1 - \frac{d_i}{p_i} \right] + \sigma_i \sqrt{T_i^*} \, E\left[\frac{d_i T_i^* - I_i^*}{\sigma_i \sqrt{T_i^*}} \right] \right\} h_i - \frac{u_i}{T_i^*} \right\}$$

If the increase in profit during the last β iterations is less than γ, then **STOP**. If $EFR_i \geq \alpha_{2i}$, then **STOP**

Step 7. Of all i, for which $EFR_i < \alpha_{2i}$, determine l, for which

$$b_l p_l T_l^* \left[1 - P\left[\frac{(I_l^* + 1) - d_l T_l^*}{\sigma_l \sqrt{T_l^*}} \right] \right]$$

is maximum

Step 8. $I_l^* := I_l^* + 1$. Go to step 3.

The basic idea of the heuristic is to allocate some capacity to a product, then compute the

corresponding optimal cycle times. Given the cycle times and the allocated capacity (represented by the target inventory level), the expected profit can be determined. If the profit is still increasing, some capacity can again be allocated to a product. Each time capacity is allocated, the ratio of productive capacity over setup capacity is increased. The product to which capacity is allocated is selected based on the expected contribution. If the profit increase drops below a critical value, the heuristic stops.

In step 1, all k_i are set at 1. This is necessary to be able to calculate the EFR_i's for the initial inventory levels in step 2.

In step 2, initial inventory levels are set at a level, such that the expected fill rate meets the minimum requirements set by a higher management level. The expected fill rate (EFR_i) formula has been deduced from Brown's partial expectation function and has been explained above. According to Brown (1963), the expected quantity short – given a certain inventory level – is the partial expectation value of that inventory level, multiplied by the standard deviation.

In step 3, the current value of the target inventory level and the integer multiples are used to determine the corresponding target cycle times. The target cycle times are comprised of the production time needed to produce up to the target inventory levels and the set-up time needed to set up a run of each product (distributed according to its integer multiple). This cycle time formula balances productive capacity and set-up capacity. Since T_i^* is both on the left hand side and on the right hand side of the equation, determining the cycle times is not straightforward. In the computer program, an iterative procedure is included, which can start with arbitrary values of T_i^*. Consecutive iterations adapt the values of T_i^* until both sides of the equation result in the same value. The starting values of T_i^* determine the number of iterations. The first time that step 3 is reached, arbitrary values of T_i^* are used. From the next time on, the most recent values of T_i^* are used as starting values.

In step 4, the integer multiples with the lowest cost are determined. In order to do this, an adapted version of the first four steps of Doll and Whybark's heuristic has been used. The adapted version is presented below

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Step A. Determine T_i independently for each product by:

$$T_i = \sqrt{\frac{2u_i}{EFR_i d_i\, h_i \left[1 - \dfrac{EFR_i d_i}{p_i}\right]}}$$

Step B. Select the smallest T_i as the initial estimate of the fundamental cycle time T:
$$T = min(T_i)$$

Step C. Determine the integer multiple k_i^- and k_i^+ for each product defined by:
$$k_i^- \le T_i/T \le k_i^+$$
where k_i^- =   the next lowest integer multiple
                 k_i^+ =   the next highest integer multiple

Step D. Determine new estimates of the k_i by evaluating the cost penalty incurred by using $k_i^- T$ and $k_i^+ T$ as the production cycle for product i. The cost for each product as a function of k, $C_i(k)$, is:

The new k_i are chosen by:

8

$$C_i(k) = \frac{u_i}{k_i T} + \frac{1}{2} h_i EFR_i d_i k_i T \left[1 - \frac{EFR_i d_i}{p_i} \right]$$

$k_i = k_i^- \text{ for } C_i(k_i^-) \le C_i(k_i^+)$

$k_i = k_i^+ \text{ for } C_i(k_i^+) \le C_i(k_i^-)$

The procedure is exactly the same as Doll and Whybark's first four steps, except for the fact that the demand rate is replaced by the expected fill rate times the demand rate. Note that Doll and Whybark's approach is aimed at a deterministic situation in which all demand will be filled. The situation under consideration in this study is characterized by a stochastic demand of which only a certain part will be filled. We use a part of their procedure to determine the integer multiples. The actual length of the cycle in their procedure is also based on cost minimization, while a more capacity oriented determination of the cycles is appropriate in this case. As shown before, the traditional ELSP procedures lead to a shorter cycle time with higher demand levels, whereas a longer cycle time is required.

In step 5 of the CCH, it is checked whether any of the multiples have been changed in the previous step. If this is the case, then the I_i^*'s must be adapted so that the expected fill rates remain the same. In general, the increase in inventory is less than proportional to the increase in k_i, since the coefficient of demand variation is smaller over longer time intervals.

In step 6, the expected profit is calculated and compared to the profit in the previous iteration. Since the function is rather flat around the maximum, the procedure is stopped if the increase in profit is less than γ/β. Determining this criterion is a strategy-related issue of the company. If this ratio is set larger, a lower overall fill rate with less investment in inventory is obtained (high return on investment). If the ratio is set very low, a higher overall fill rate is reached at the expense of an increase in inventory. In this last case, the profit may be hardly different from the profit with a low ratio, but the ROI will be much lower. Note that a considerable increase in target inventory level will be needed to increase the service level marginally, since the tail of the distribution function needs to be considered. The target cycle time will not be increased extremely, because the extra quantity to be produced each cycle is only marginal; due to the small increase in fill rate, most of the extra inventory will be left at the end of the cycle.
In this step, it is also checked whether all of the products have reached their respective maximum required service level.

In step 7, the product is selected which has the greatest expected contribution per unit of capacity for the next unit produced of this product. Only products that have not yet exceeded the maximum service level can compete. The selected product will be the one for which the target sales rate will be increased.

In step 8, the target inventory level of the product that was selected in the previous step, is increased by 1. After this, the heuristic continues with step 3, where the cycle times are recalculated with the new value of one of the target inventory level. When the heuristic is finished, it provides the operations manager with the target inventory levels and the corresponding target cycle times.

6. Simulation Experiments
Simulation experiments have been conducted to investigate the performance of the capacity coordination heuristic under different operating conditions. In these experiments, five different products are manufactured using a single step process. The product change-over times and the

production rates are fixed and are the same for each product. The set-up times are not sequence dependent. The available production capacity is limited and overtime is not allowed. The CCH is benchmarked against an elementary stable cycle times heuristic (SCT). The SCT is described below.

Step 1.	Calculate target cycle times, according to Doll & Whybark (1973).
Step 2.	Select the product with the shortest run-out time (ROT as in Exhibit 3.4).
Step 3.	Produce the selected product in the following quantity:
	$$d_i\,T_i^{*} - I_i$$
Step 4.	When a production run has been finished, return to step 2.

The SCT was compared earlier to a heuristic using variable cycle times (VCT) in Fransoo (1992) and showed a much better performance than this VCT.

Experimental Setting

Four levels of capacity tightness are operationalized in terms of the ratio between the total demand rate and the production rate. The four levels examined are 83.3%, 87.5%, 91.7%, and 95.8% of the production rate. Any demand rate which is greater than or equal to the production rate is not feasible for Doll and Whybark's procedure. Additionally, two demand level are operationalized for the CCH only: 100.0% and 104.2%. For all products, the demand is distributed normally. The demand variance is set proportional to the average, i.e., the coefficient of variation is held constant at 0.33. The product data used in the experiment are presented in Table 1.

Table 1 *Problem data for the simulation experiments*

Product		a	b	c	d	e
Production rate	p_i	240	240	240	240	240
Setup time	c_i	0.208	0.208	0.208	0.208	0.208
Contribution/unit	b_i	$ 4	$ 5	$ 6	$ 8	$ 9
Inv.Cost/unit/period	h_i	$0.04	$0.05	$0.06	$0.08	$0.09
Setup Cost	u_i	$ 150	$ 150	$ 150	$ 150	$ 150
Average demand (83.3% level)	d_i	80	40	40	20	20
Average demand (87.5% level)	d_i	84	42	42	21	21
Average demand (91.7% level)	d_i	88	44	44	22	22
Average demand (95.8% level)	d_i	92	46	46	23	23
Average demand (100.0% level)	d_i	96	48	48	24	24
Average demand (104.2% level)	d_i	100	50	50	25	25

Two approaches are examined: a hierarchical approach based on ELSP lotsizing (SCT) and a hierarchical approach based on CCH. The objective of the current experiment is to test whether a policy which has a more advanced long-term capacity coordination function performs better than a policy which is based on an elementary ELSP heuristic for determining the cycle times. Especially at high levels of utilization, good control of the cycle times will make sure that productive capacity will not be spent on setting up. This will result in a higher fill rate and more contribution. On the other hand, inventory costs may rise. We realize that the tests are only performed under a limited variety of environmental settings. However, we think that this will be sufficient to make the major effects clear.

Model Dynamics
Under the SCT, the target cycle times are pre-calculated using the procedure developed by Doll and Whybark. The target cycle times are used as decision parameters at the operational decision level.

The order acceptance decisions are taken at the beginning of each period. The daily demands for the five products are presented in a random sequence. This eliminates any built-in acceptance bias. Backordering is not allowed; any demand that is not directly met from stock gets lost. The on-hand inventory balance is adjusted to reflect the order acceptance decision. The on-hand inventory balance is increased at two possible events. The first one is the start of a new period. At this moment, just before the order acceptance takes place, the inventory balance is updated with the quantity manufactured since the previous update. The second event is the completion of a production run. Also at this moment, the inventory balance is updated with the quantity manufactured since the previous update. At the end of each production run, the product with the minimum run-out time is scheduled for production. The production quantity is based on the net requirement, which is defined as the expected demand during the cycle time minus the actual inventory position.

Under the advanced policy, the target cycle times and target inventory levels are precalculated using the CCH.

At the beginning of each period, after the order acceptance decision has been taken (in the same way as under the SCT), the next product is scheduled for production. We use a fixed sequence, i.e, the products are produced in the sequence a-b-c-d-e-a (etc.). The production quantity is based on the net requirement, which is defined in the same way as under the SCT.

For each policy, five demand sequences are replicated by using five common random number seeds. For each demand sequence, the system is operated for 3,000 periods initially, at which time the performance measures are re-initialized. This length is chosen based on an analysis of different run lengths to achieve steady state. The system continues to operate thereafter for another 3,000 periods. At the end of these 3,000 periods, statistics are recorded and performance measures are re-initialized to zero.

Experimental Criteria
In these experiments, we measure the system performance using two primary performance measures: profit and fill rate. The profit is defined as the contribution margin of all products delivered minus the inventory cost minus the set-up cost. As has been discussed above, the maximization of profit is the primary objective of a business. The fill rate of a product is defined as the number of products that are delivered (accepted) divided by the number of products demanded. The actual fill rates are used to analyze the internal behavior of the system.

The experiments reported on in this paper have several purposes. First of all, we are interested in the increase in performance of the system compared the the SCT approach. The required system performance is two-fold: profit and fill rate. We expect an increase in profit due to the introduction of the *target inventory level* for each product. We also expect a considerable improvement in fill rate, especially regarding the required distribution of the fill rate over the various products.

Another important subject in which we are interested is the predictive value of the long-term capacity coordination model. We have referred to this issue in our introduction as *internal validity*. If this model represents the operational production system well, the profit prediction and fill rate predictions should approximate the actual profit and fill rates which are realized.

11

Experimental Results
Table 2 presents the profit results of the SCT and CCH in the first two colums for the six demand levels investigated. The third column shows the profit as it was predicted by the CCH (value of the objective function according to equation 3).

Table 2   *Simulation results: Profit using SCT and CCH under six different demand levels. In the far right column the value of the long-term objective function can be found.*

Demand Level	SCT	CCH	CCH(obj.)
83.3%	$2,708,609	$2,727,514	$2,777,380
87.5%	$2,953,466	$2,951,418	$2,994,784
91.7%	$3,171,237	$3,163,615	$3,198,158
95.8%	$3,249,536	$3,309,703	$3,304,387
100.0%	–	$3,337,337	$3,328,766
104.2%	–	$3,412,003	$3,338,522

From Table 2 we may conclude that the difference in profit between the two policies CCH and SCT is not very large. The increase in profit is highest at the highest demand level where both policies have been tested (95.8%). At the three lower demand levels (83.3%, 87.5% and 91.7%) the expected fill rate EFR_i – generated by the CCH – equalled the maximum fill rate α_{2i} for all five products. Apparently, if nearly all demand can be delivered and the cycle times are kept stable at the operational level, the more advanced algorithm at the tactical level does not result in better parameter settings. As long as the capacity is not too tight, the modified Doll and Whybark procedure generates good settings for the cycle times. However, if the demand level increases further, the performance of the parameter setting provided by the modified Doll and Whybark procedure decreases as compared to the performance of the parameter setting provided by the CCH. The SCT cannot be used at demand levels greater than or equal to 100%.

In the introduction we have stated that the internal consistency of the model is an important performance indicator. Usiñg the SCT policy, we have noted in earlier experiments that the fill rates of each of the individual products are not controlled by the parameter settings at the higher level. The individual fill rates were strongly influenced by the share in the total demand of each product: the fill rate was relatively high for product with a high demand rate and lower for products with a lower demand rate (Fransoo 1992 and 1993).

Under the CCH, each of the products gets its own setting for the target inventory level. Based on this target inventory level and the target cycle time, an expected fill rate can be calculated at the long-term decision level (see equation 2). In Table 3, the expected fill rates and the actual fill rates for each of the six demand levels are presented.

Table 3 *Simulation results: Expected and actual fill rates for each product for six demand levels under the CCH. Also, the fill rates under the SCT are presented.*

Product		a	b	c	d	e
Demand Level						
83.3 %	Exp.	99.0	99.2	99.2	99.3	99.3
	Act.	98.0	97.9	97.7	98.1	98.3
	SCT	98.2	97.4	97.4	96.1	96.2
87.5 %	Exp.	99.1	99.1	99.1	99.1	99.1
	Act.	98.0	97.9	97.8	98.1	98.1
	SCT	98.8	98.2	97.9	96.8	96.8
91.7 %	Exp.	99.1	99.1	99.1	99.2	99.2
	Act.	98.0	98.3	98.4	98.3	98.2
	SCT	99.2	99.0	98.9	97.8	97.7
95.8 %	Exp.	96.4	97.6	97.9	98.7	98.7
	Act.	96.6	97.5	97.9	98.8	98.7
	SCT	96.6	95.9	95.6	93.0	93.3
100.0 %	Exp.	88.2	93.2	95.4	97.3	97.3
	Act.	88.4	93.0	95.1	97.2	97.0
104.2 %	Exp.	82.6	92.1	94.9	97.3	97.3
	Act.	83.3	92.0	94.7	97.0	96.8

The results presented in Table 3 show that the internal validity of the long-term model is very high: the expected fill rates, which were calculated based on an aggregate model of the operational decision function, appear to give a good prediction of the actual fill rates at the operational decision level. This is an important feature of the model we have developed, namely that it enables the managers at the tactical decision level to determine target inventory levels and target fill rates which can be realized using a very simple operational scheduling procedure.

7. Discussion

The long-term capacity coordination decision has two function within an organization:
- Coordination of the manufacturing and marketing departments
- Coordination of long-term and short-term decisions

The proposed coordination method aims at providing support in solving the natural conflict of interest between marketing and manufacturing. In line with the work of Konijnendijk (1992), we recognize that this conflict should be discussed at the tactical decision level. In this way, the day-to-day operations are not disturbed by this conflict of interests. The management should take these tactical decisions, since these involve priority setting and capacity allocation. In a business context, this is comparable to the determination of the annual sales and production plans (which are sometimes referred to as sales and production budgets). The priority setting does not only

involve the priorities between the various products, but also the priority setting between inventory and service, and between set-up and inventory. If these trade-offs are made on a tactical decision level, then the theoretical model shows that the operational decisions can be simple.

This simplicity is caused by the fact that the key parameters have been decided upon at the higher decision level. The hierarchical approach presented here has two clear organizational differences. First, it decides on priorities *at the tactical decision level*. At the operational decision level, no trade-offs are made. Second, it determines control parameters at the tactical decision level, which serve as targets for the operational decision level. This enables the operational decision level to account for long-term effects.

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