DESIGN OF A PERIOD BATCH CONTROL PLANNING SYSTEM FOR CELLULAR
MANUFACTURING

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ABSTRACT: Period Batch Control is a production planning system that decomposes the cellular manufacturing system into N stages and gives each stage the same amount of time P to complete the required operations. Applying the PBC system in combination with cellular manufacturing is said to result in short and reliable throughput times, and low inventory costs. However, the design of the PBC system, i.e. the size of N and P, does not follow directly from the cellular organization. We show that varying the values of both the number of stages N and the period length P greatly influences the performance of PBC. Furthermore, if both N and P have been determined, system performance is still very sensitive for different allocations of operations to the stages. We present a mathematical programming model that determines an optimal allocation of operations to stages, using a longest path orientation accompanied by a bottleneck orientation.

INTRODUCTION

Period Batch Control (PBC) is a production planning system that has been proposed for application within cellular manufacturing.[Burbidge,1996; Hyer and Wemmerlöv, 1982] The PBC system supports the transparency needed to effectively exploit the advantages of the cellular organised manufacturing system. Reported advantages are reliable throughput times that facilitate a reduction of the lead times, smaller work in progress, and increased autonomy within cells. Figure 1 shows the structure of the PBC planning system.

The PBC system uses the same manufacturing throughput time T for all products. The period before the orders are released to the production floor is the ordering period O. This period is used for ordering raw material and required parts, controlling designs and required tools, etcetera. The products for which these activities are performed have entered the system during the order acceptance period AC. A program meeting at the end of this period determines if specific actions (such as hiring extra capacity) have to be undertaken in order to complete these orders within the total throughput time. Work orders for products are released to the production system at the end of the ordering period O. The operations that are allocated to the first stage are being performed during the next period. At the end of the period, all finished work is positioned in the decoupling stock. Bought parts that are required in the next stage will also be available at the start of the next period. The new period allows production activities on operations of the products that entered the system at time 0 and were allocated to stage 2. Note that these

<table>
<thead>
<tr>
<th>Order accept.</th>
<th>Ordering</th>
<th>PBC: N=3 stages</th>
<th>Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>O</td>
<td>T=N*P</td>
<td>S</td>
</tr>
<tr>
<td>Program meeting</td>
<td>P</td>
<td>Production process</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Stage 1</td>
<td>Stage 2</td>
<td>Stage 3</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>2P</td>
<td>3P</td>
<td>4P</td>
</tr>
<tr>
<td>0</td>
<td>5P</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

L=(N+2)*P  P=Period length  T=Manufacturing throughput time  L= Order lead time

Figure 1 Manufacturing throughput time T=N*P
operations may belong to the same cell. Stage boundaries and cell boundaries need not be identical. Hence, cells may at a specific moment in time receive work that were released to the system at different program meetings. If the product has been completed in the final stage N, it is available for sales and delivery. Assuming that the mean arrival time of an order in period AC is $-\frac{1}{2}P$ and its mean departure time is half way the sales period, the mean order lead time is $(N+2)*P$.

Recent comparisons of PBC with other planning systems, such as MRP and JIT, show that PBC systems perform relatively well in production situations that face high demand variations. [Steele, Berry, Chapman, 1995] However, the performance dramatically detories if the cells are not able to finish the work within the period length P. They suggest that this detoration may be caused by large setup times and long total processing times or lot sizes. The problem might be solved by allowing different internal lead times for production orders. However, this influences the regular loading of the system. As this periodicity is essential for the PBC system, we have to find another way to design PBC systems that are less sensitive for this detoration in order to be still able to exploit the advantages of cellular manufacturing systems. Crucial in this design problem is to let the makespan in the N succeeding stages in the PBC system be smaller than the period length. If the stages in the PBC system are designed such that the makespans are generally below P, even if demand variation is high, than the system may be considered to be fairly robust. In general, if a redesign of a PBC system leads to a reduction in the required amount of overtime, the redesign is considered successful.

Literature on the design of PBC systems does not give much support to the determination of suitable values for the number of stages N and the period length P. Both Burbidge and New emphasise the importance of small values for N as well as P, because this will lead to reduced throughput times and smaller inventory levels,[Burbidge, 1996; New, 1977] They suggest to let the length of P be such that there is enough capacity for the total setup and processing time that is required and such that a complete batch of each part can be produced within this period length. Note that the total processing time within a stage depends on the period length P, as doubling of the period length will lead to a doubling of the total processing time within the stage. This complicates the determination of a suitable value for P, as was discussed in [Riezebos, 1997]. The suggestions on the length of P are therefore too general to be of practical use when designing a PBC system.

The determination of N is in literature on PBC strongly related to the cellular organisation of the manufacturing system. This literature states that the PBC system is designed such that sequentially dependent cells are allocated to subsequent stages in the PBC system. (Cells are sequentially dependent if at least one product requires subsequent processing in both cells,[Riezebos and Gaalman, 1995]) Here the advantage of combining PBC for planning of the manufacturing system with the use of a cellular organisation for the manufacturing system becomes clear. Without a cellular organisation in which different machinery is combined into one cell in order to produce a sequence of operations in one organisational unit, the different operations would all require a separate stage in the PBC system. This would greatly increase the number of stages N and hence the throughput time $T=N*P$ of the PBC system.

Although the design of cells is subject of a separate analysis (e.g., Product Flow Analysis [Burbidge, 1989]), PBC assumes that they are designed such that during production no back flows between cells occur. This leads to the conclusion that the number of stages in PBC is an externally determined input for the design of the planning system. However, reports on the implementation of PBC in industry suggest that considering the possibility of eliminating stages is an important phase in the design of PBC.[Burbidge, 1993; Burbidge, 1996; New, 1977] Stages can be eliminated by combining several sequentially dependent operations that are performed in different cells into one stage. If these operations can still be finished within one period of length P, total throughput time has decreased with one period length P. Note that here the distinction between cell boundaries and stage boundaries becomes evident. In the remaining part of this paper we will give more attention to this phenomenon and explore the benefits of alternative allocations of operations to stages that do not take the cell boundaries as leading principe in designing the PBC system.
Practical PBC design projects combine the above mentioned design principles with many pragmatic and context dependent insights. Descriptions of such insights can for example be found in [Burbidge, 1988] and in [Melby, 1994]. However, the principles and guidelines do not provide a fundamental insight in the factors that have to be taken into account when determining N and P. The main objective that underlines the design principles is to reduce the manufacturing throughput time T=N*P. However, T can be reduced in several ways. For example, we can reduce N and let P slightly increase, or reduce P and increase N, or we can reduce both. The consequences of these reduction programs have to be considered carefully, as they will not only lead to changes in the manufacturing throughput time T, but also in the organisation of the planning process, customer service, and performance of the PBC system in terms of the amount of overtime required.

In this paper we analyse the interdependency between N and P and determine conditions that favour specific combinations of values for N and P. We will do this under the condition that the product of N and P is held constant. If we hold T=N*P constant, we will get insight in the fundamental design choice between a system with a small number of stages N and a relatively long period length P, and a system with a high number of stages N and a small period length P. The second part of this paper will further explore the PBC design phase after N and P have been determined: the allocation of operations to the stages. We present a mathematical programming model that supports this allocation of operations. Finally, we summarize our conclusions at the end of this paper.

**TRADE OFFS BETWEEN N↑ P↓ AND N↓ P↑**

Figures 2 and 3 illustrate the situations that we distinguish. Figure 2 shows a configuration of a PBC system with N=2 and P=1½ (N small, P large) and figure 3 has N=6 and P=½ (N large, P small). Both systems have T=N*P=3.

Table 1 presents the results of this evaluation. The left side of the table describes the expected positive effects in case PBC systems use a small number of stages with a relatively large period length. The same effects could be viewed as negative effects at the right side of the table. We have restricted ourselves to describing the positive effects at both sides of the table.

Many positive effects for the organisation and utilisation of the process in case P increases are known from literature. To summarise, an increase in P makes a higher utilisation of the various processes possible, as it reduces the start/finish effect and the setup time effect. However, this does only hold if the number of operations that have to be performed within a stage remains constant. If an increase in P is combined with a decrease in N, the operations in the eliminated stage(s) have to be allocated to other stages. This redistribution may have negative effects on the start/finish losses and coordination efforts, as we will see later.
<table>
<thead>
<tr>
<th>Factor</th>
<th>N small, P large</th>
<th>N large, P small</th>
</tr>
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<tbody>
<tr>
<td>Input</td>
<td>Increased mix flexibility</td>
<td>Less material in process through just-in-time delivery</td>
</tr>
<tr>
<td>Process</td>
<td>Less sensitive to long processing times</td>
<td>Higher utilisation of bottlenecks</td>
</tr>
<tr>
<td></td>
<td>Less occurrence of start/finish losses</td>
<td>Smaller start/finish losses</td>
</tr>
<tr>
<td></td>
<td>Less set-up time losses</td>
<td>Less close-scheduling effort</td>
</tr>
<tr>
<td></td>
<td>More attractive work packages</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>Less programming efforts</td>
<td>Better progress control</td>
</tr>
<tr>
<td></td>
<td>Better synchronisation</td>
<td>Easier coordination of subcontracting</td>
</tr>
<tr>
<td></td>
<td>Easier coordination of shared resources</td>
<td>Easier coordination of shared resources</td>
</tr>
<tr>
<td></td>
<td>Easier sequential coordination between cells</td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>Less forecasting effort</td>
<td>Less finished stock</td>
</tr>
<tr>
<td></td>
<td>More levelled demand variations per period</td>
<td>Smaller order lead time</td>
</tr>
</tbody>
</table>

The control and coordination effort within a stage increases as a consequence of the increase in close-scheduling requirements in case of larger P. The informal planning system within a stage has to cope with this coordination, as PBC does not support the planning within a stage. In general, a larger P results in more operations per stage and more precedence relations between these operations that have to be count for within a period. This increases the coordination effort within a period. As the length of the period is longer and PBC progress control takes place at the end of a period, the increased coordination effort per period is combined with a reduced transparency of the planning system and less monitoring performance.

Moreover, if there are subcontracting activities necessary that succeed operations within the stage, the coordination of these activities becomes more problematic in case P is larger, due to the loss of predictability and transparency. The same holds for the use of shared resources. Increase of N makes it easier to isolate such activities or resources in a single stage and hence reduces the coordination effort. The focus of the coordination of such activities and their relation with other elements of the production system changes to coordination between the stages, and PBC accommodates this sequential coordination through its synchronisation mechanism.

However, an increased number of stages makes it necessary to organise more frequently a program meeting for determination of the production program in the subsequent period. This requires more time from management, more information gathering and forecasting effort, but it leads also to a better progress control.

Finally, we consider the factor output of table 1. PBC systems with small N and large P are less sensitive for variations in demand. However, systems with smaller periods have to invest less in finished stock and are able to deliver their customers more frequently.

**ALLOCATION OF OPERATIONS TO STAGES**

One of the important decisions after determining the number of stages N and period length P in a PBC system concerns the allocation of operations to the stages, i.e. the contents of the various stages. The allocation of operations to stages influences the start/finish losses, bottleneck utilisation, subcontracting coordination problems, and investment in working capital. Other effects, such as the setup-time effect, are not affected by the allocation of operations. They only depend on the number of stages or on the length of P.

We will illustrate the problem of determining the contents of a stage with figure 5. This figure shows an alternative allocation of operations to stages compared to figure 2 (identical to figure 4).
The reallocation of operations affects the workload distribution of resources over the period. The two subsequent operations e and f were allocated to different stages, but are now allocated to the same stage. Hence, operation f cannot start at the beginning of a period, which was possible when both operations were allocated to different stages. This has consequences both for the earliest start time of succeeding operations in stage 2 and for the latest finish times of the preceding operations in stage 1. Therefore it affects the workload distribution of the resources that perform these operations.

Literature on PBC does not give much attention to the allocation of operations to stages. As was mentioned before, there is a tendency to assume that all operations that have to be performed within a cell are allocated to the same stage. However, there are two main disadvantages of such an allocation. First, holding costs increase, as this allocation does not distinguish between operations that require further processing in next stage and operations that will have to wait a complete period before they will proceed. Second, overtime costs or transfer batch costs increase, as this allocation does not take into account the total time required for the sequence of operations that has to be completed within a period. Finally, such an allocation does not take into account specific problems that occur due to the periodic loading of the system. Start/finish losses on bottleneck machines in the cell may be avoided by allocating these operations to a separate stage. Hence we conclude that in general it is not necessary to allocate all operations that are to be performed in the same cell to the same stage.

Thus the question remains what factors have to be taken into account when determining the allocation of operations to stages. We distinguish the following factors:

- timing of increase in working capital
- effects of sequence dependent operations within a stage
  - organisational impact
  - time required for sequence of operations (longest path orientation)
  - timing of workload arrival at bottleneck resources (bottleneck orientation)

The allocation of operations to cells determines where the operations are being performed. The allocation of operations to stages determines when the operations are performed. We assume that we know which operations in what sequence where have to be performed in order to obtain a product.

**Timing of the increase in working capital**

This is the first factor that we consider in determining the stage allocation. If purchased material is required as input for an operation, then costs increase with a lower stage to which this operation is allocated. If all operations for this product are performed in stage N, the purchased material has only to be available one period before the end product is sold to the customer. However, if operations are allocated to stage 1, the purchased material for these operations has to be available at the start of this period. That material will reach the customer in sales period N+1 and hence will be on the working capital list during N periods or more. Hence, the allocation of operations to stages affects the timing of the increase in working capital. The lowest cost solution is to allocate all operations to stage N.
Effect of sequence dependent operations within a stage

If there were no precedence relations between operations, all operations can be allocated to the final stage N. There would be no need for sequential coordination between cells, as all operations can be performed independently. However, in general precedence relations do exist between operations, which makes these operations sequentially dependent. We will give attention to three facets of sequential dependent operations within a stage.

**Organisational impact.** The allocation of operations to stages influences the complexity of scheduling within a period. If sequentially dependent operations are allocated to the same stage, the scheduling function within the stage has to coordinate the timing of the subsequent operations, as the latter can only start if the former has finished. The coordination effort that is introduced through the allocation of sequentially dependent operations within the same stage varies per situation. We assume that it generates more problems if the sequential dependent operations are performed within different cells, i.e. if the cells are sequentially dependent within the stage. The problems we expect to occur are, amongst others, related to responsibility for (internal) due date performance, utilisation of cell equipment, and lay-out issues within and between cells. The dependent cell has less sight on the exact arrival time of the material for the next operation that it has to perform.

Allocating sequential dependent operations to different stages if they are performed in different cells is not the only possible solution. An alternative is to decouple the cells with internal due dates in order to allow both cells enough time to finish the operations. Such a solution restricts the scheduling possibilities of both cells and may even cause a cell to perform a setup for a machine twice during a period, thus reducing the benefits of the synchronised period batch control approach. On the other hand does such a solution reduce the investment in working capital.

We conclude that there is a greater organisational impact if sequential dependent operations that are performed in succeeding cells are allocated to the same stage. If such operations are allocated to succeeding stages, then both cells will have the complete period to finish the operations and no explicit coordination efforts will be required between the cells during the period.

**Time required for the sequence of operations (longest path orientation).** The larger this time, the more sensitive the system is to volume and mix variety. The piling up of processing times leads to a higher possibility of facing tardiness. The possibility of introducing tardiness in the system increases if the allocation of operations to stages generates longer paths of subsequent operations. Close-scheduling can only partially solve this problem. The occurrence of long paths of subsequent operations within the same stage reduces the possibility of developing stable standard sequences / schedules in the various cells, which was again one of the ways to achieve the benefits of period batch control. Hence, a proper allocation of operations to stages has to allow enough slack time per stage to cope with the long paths caused by sequentially dependent operations within the stage.

**Timing of work load arrival at the bottleneck (bottleneck orientation).** We can regulate the loading of a bottleneck with the allocation of operations to the stages. If a bottleneck receives too much work that can only be performed during the second part of a period, a redistribution of preceding operations to an earlier stage may solve these problems. Note that the precedence structure between operations that have to be performed in the same period changes due to this redistribution, but the product structure is not altered. We already have illustrated this with figure 4. The machine that performs operation e first had to wait until all preceding operations (a,b,c,d) were finished. In the alternative allocation of figure 5 these preceding operations were completed in the preceding stage, so at the start of a new period the machine can immediately begin to process this operation e, although nothing has changed in the precedence structure of the product itself.

The above mentioned factors will be explicated in a mathematical model in the next paragraph.
In order to facilitate the allocation of operations to stages, we have developed a mixed integer programming model that explicates the relevant factors for determining the contents of the stages. Having introduced the longest path orientation of the model and the nomenclature we use, we discuss the model, and finally we extend the model with a bottleneck orientation that may be useful in designing a PBC system.
The mixed integer programming model allocates operations to stages such that the investment in working capital is minimized (objective function (1)).

An operation \(i_h\) that is allocated to stage \(j=1\) will add \(C_T \cdot V_{i_h} \cdot d_h\) to the total cost of working capital.

If this operation had been allocated to stage \(j=N\), the added cost would have been \(\frac{(C_T \cdot V_{i_h} \cdot d_h)}{N}\).

However, the allocation of operations to stages is restricted.

First, we define the occurrence-constraint. An operation has to be allocated to at least one stage in order to let the production system perform the operation. Constraint (2) together with condition (6) that \(x_{ij}\) is a binary variable ensures that the operation has to be allocated to one and only one stage. The uniqueness of stage allocation is a consequence of PBC.

Precedence relations between operations make that if an operation \(i\) is allocated to stage \(j\), then none of its followers \(l\) may be allocated to an earlier stage. Constraint (3) ensures this precedence-feasibility of the solution.

The reason why not all operations can be allocated to the final stage \(N\) is that the allocation has to be time-feasible as well. If too much sequentially dependent operations are allocated to the same stage, this may cause tardiness to occur. Constraints 4-5 determine the tardiness in a stage due to the sequential relations between operations in the same stage, and the objective function minimizes the tardiness. The non-negative variable \(t_{i,j}\) describes the earliest start time of an operation \(i_h\) in stage \(j\).

Constraint 4 sets the earliest start time of an operation \(l\) with a predecessor \(i\) in the same stage to be not smaller than the earliest start time of this operation \(i\) plus the total amount of setup time and processing time required for the whole batch of \(i\). If both operations are not performed in the same cell, then the earliest start time of the latter operation \(l\) is further delayed with \(CD\), a cell delay (policy) factor, which represents the organizational impact of such an allocation. If \(i\) and \(l\) are not allocated to the same stage \(j\), then the use of the big M factor causes the constraints 4 to become non-binding.

Constraint 5 ensures that the earliest finish time of any operation in stage \(j\) will not exceed a specified percentage of the period length \(P\). This percentage depends on \(MI\), the machine interference delay, which is expected to correct for delays that may occur in processing a sequence of operations due to the waiting times on availability of machines. If more time is needed in a stage, then the tardiness is assumed to become positive, which increases costs. The objective function tries to minimize costs and hence a solution without tardiness will be preferred.

The solution that is found with our model may not be the most cost-efficient allocation of operations to stages, as we neglect the possibility of shortening the time delays between succeeding operations.

Note that the we have not considered machine capacity as a dominant factor in allocating operations to stages. In a unicycle PBC system, the machine obtains each period the same amount of work. If we assume that demand is as expected, then the allocation of operations to stages does not influence the amount of work per machine, only the timing of earliest arrival at and latest departure from a machine. Therefore, stage allocation may cause temporarily overloads of work at a machine. However, the prediction of such occurrences is quite difficult. If this type of problems cannot be solved at cell level, we should add a bottleneck-orientation to the longest-path orientation that we have described so far.
A **bottleneck-orientation** has to be applied if the utilization of a bottleneck is a dominant design principle in PBC system design. A bottleneck-orientation gives attention to the loading of machines during a period. Bottleneck problems can be solved with methods from single machine scheduling with release dates and due dates.[Carlier, 1982] Our bottleneck-orientation to stage allocation consists of the inclusion of constraints that try to determine if the bottleneck will exceed its capacity limits. The extra constraints and variables for the mixed integer model are presented above.

Constraint 7 ensures that the time delays in stage j are zero if the operation is not performed within stage j. Constraint 8 determines the remaining time in stage j after finishing operation i_h at the bottleneck. If the operations i_h and l_h ∈ F_i are performed in different stages, the remaining time is zero, but if they are performed in the same stage, then we have a positive remaining time. This restricts the scheduling capabilities on the bottleneck. Constraints 9-11 give attention to this problem. For any subset of operations that have to be performed at the bottleneck we determine the earliest release time, add the total setup time and processing time of this subset at the bottleneck, and finally add the minimal remaining time in this period (at other machines) after finishing this subset at the bottleneck. This sum may never exceed the period length P. All variables are non-negative (12).

The number of constraints increases rapidly as the cardinality of B_k increases. However, we need not check every subset K ⊆ B_k. We may restrict our attention to subsets of operations that may cause MinHead and/or MinTail to be non-zero, as this might result in an infeasibility with respect to bottleneck capacity. This reduces the number of subsets to be considered.

Due to the specific structure of the sparse matrix of the mixed integer model (a large part of it has a structure similar to a uni-modular matrix) an optimal solution is easily found. We have used the Super Lingo software from Lindo Systems Inc. to test this model. The limits of this version are a maximum of 1000 variables and 500 constraints. On a Pentium II 266 personal computer it took less then 2 seconds CPU time to solve problems with approximately this number of variables and constraints. Note that practical implementations of the model should better use a tailor made algorithm that allows solving much bigger allocation problems within reasonable time. Note also that if products have an identical product structure, but different setup- or processing times, a simplified allocation can be performed with this model by applying the same allocation of operations to stages for all these similar products. An example of such a simplified allocation is presented in figure 6.

**Define**

- \( B_k \) = Set of operations \( i_h \) that have to be processed at bottleneck machine \( k \)
- \( K \) = Subset of operations: \( K \subseteq B_k \)
- \( f_{i_h,j} \) = minimal remaining time in stage \( j \) after finishing operation \( i_h \)
- \( \text{MinHead}_k \) = minimal waiting time before bottleneck can start with subset \( K \) of operations
- \( \text{MinTail}_k \) = minimal remaining time after finishing subset \( K \) of operations at bottleneck

**Model**

\[
\begin{align*}
\text{(7)} & \quad f_{i_h,j} & \leq M \cdot x_{i_h,j} & \quad \forall i_h \in B_k, j = 1..N \\
\text{(8)} & \quad f_{i_h,j} + M \sum_{r=1}^{N-1} x_{i_h,r} & \geq f_{i_h,j} + s(l_h) + d(l_h) \cdot p(l_h) + I_{i_h} \cdot CD - M \sum_{r=j+1}^{N} x_{i_h,r} & \quad \forall i_h \in B_k, l_h \in F_{i_h}, j = 1..N \\
\text{(9)} & \quad \text{MinHead}_k & \geq t_{i_h,j} & \quad \forall i_h \in K, j = 1..N \\
\text{(10)} & \quad \text{MinTail}_k & \geq f_{i_h,j} & \quad \forall i_h \in K, j = 1..N \\
\text{(11)} & \quad \text{MinHead}_k + \sum_{i_h \in K} [ s(i_h) + d(l_h) \cdot p(l_h) ] + \text{MinTail}_k & \leq P & \quad \forall i_h \in B_k, j = 1..N, K \subseteq B_k
\end{align*}
\]

\( \text{MinHead}_0, \text{MinTail}_0, f \)
The data for the product structure in this allocation is obtained from the study of [Steele et al., 1995]. We have used a manufacturing throughput time $T=7200$ minutes and bottleneck machine 13.

The optimal stage allocation is presented in figure 6. We see that for $N=3...6$ the bottleneck is allocated to a separate stage in order to reduce the start/finish losses that occur due to the periodicity of the PBC system. Operations 14 and 15 are performed in the same cell as the bottleneck operation 13. If these operations would be allocated to the same stage as the bottleneck operation, we would face much higher amounts of overtime work. The optimal allocation procedure therefore does not treat the cell boundaries as leading in the design of the PBC system, as suggested in literature on PBC, but it also considers the loading patterns that will occur in the system. This leads to a different allocation of operations to the stages.

**Figure 6:** Optimal stage allocation of operations for $N=1,2..,6$; bottleneck machine 13.
CONCLUSIONS

The determination of N and P is essential in the design of a PBC system. We have shown that systems with a small number of stages and large period lengths will be preferred if the formal control effort (program meetings and forecasting effort) has to be restricted. The overall demand flexibility of the system can be higher and if cells are able to cope with the remaining coordination problems, the system may operate adequately.

On the other hand, systems with a large number of stages and a small period length depend more on the synchronization of PBC in controlling the work flow. The design of PBC in terms of the allocation of operations to stages may make it possible for several critical operations to operate rather independent from the rest of the system. The performance in terms of inventory costs, overtime work, and order lead time, increases if the allocation of operations to the stages is performed well.

The allocation of operations to stages is an important phase in designing the PBC system after N and P have been determined. The allocation influences a number of performance measures, such as costs and tardiness. The mixed integer model explicates the decisions on stage allocation. The basic model uses a longest path orientation in the allocation of operations to stages. The model can easily be extended to facilitate a bottleneck orientation.

The optimal allocation procedure shows that there is no need to treat the cell boundaries as leading in the design of the PBC system, as suggested in literature on PBC. We should also consider the loading patterns that will occur in the system. This may lead to different allocations of operations to the stages.

REFERENCES


Melby, O.H., Implementation of Period Batch Control in a job shop (in Norsk), Norwegian institute of technology, University of Trondheim, 1994.


Riezebos, J., Gaalman, G.J.C., Relations between cells in cellular manufacturing, SOM Research report 95A45, University of Groningen, 1995.

