Cyclic Planning

by

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Abstract:

This paper discusses cyclic planning. The underlying idea of cyclic planning is to use cyclic schedules for long term planning and coordination. Cyclic planning is applicable in many environments and has the potential to simplify production management and to increase the efficiency of manufacturing. We argue qualitatively that significant benefits result from easier scheduling, improved material handling, shorter production leadtimes, reduced planning and control costs, decreased buffer inventories, easier order booking and other improvements.

The paper discusses different uses and forms of cyclic planning, and its costs and benefits. A simulation of a job shop is presented to illustrate the favorable effect of cyclic planning on leadtimes. In addition, two case studies conducted by the authors are presented and discussed.
Section 0 Introduction

There are a variety of approaches to planning and scheduling production, ranging from sophisticated mathematical algorithms to managerial and organizational techniques. Many recent innovations in manufacturing fall within the last category, for example, the "just-in-time" philosophy, Kanban, continuous flow manufacturing, period batch control, and group technology.

During the past two decades there have been significant efforts to understand, develop, and apply these concepts. Understanding the ideas that underlie these approaches has contributed to a deeper knowledge of the principles of manufacturing, and changed production management. For example, fundamental principles newly appreciated include the importance of simplifying material flow and layout, reducing arrival and processing rate heterogeneity, improving quality, and decentralizing production control.

This paper studies one of the techniques used by practitioners, called cyclic planning that has many of these features. Cyclic planning uses a fixed cyclic schedule to help a firm coordinate its activities and plan production. Cyclic planning coordinates production by temporally reserving process steps to products in a preassigned, cyclic way. The reservation patterns for production resources have an identical period (which we will refer to as the cycle time) and are synchronized to minimize waiting time for the jobs in the system. The cycle time is chosen for convenience and may be a day or a week or longer.

This paper focuses on the benefits of using cyclic schedules. There is an extensive research literature on cyclic scheduling, which derives repeating short term schedules that minimize set-up and holding costs. In contrast, this paper studies the long term benefits of cyclic schedules that transcend holding and set-up cost reduction, particularly lead time and customer service. To differentiate our objective from that of the latter literature, a distinction between cyclic planning and cyclic scheduling. In our use, the term cyclic planning recognizes the long term strategic benefits that arise when using cyclic schedules, in excess of holding and set-up cost reduction. We emphasise that many long term organizational benefits are available that are not considered by the cyclic scheduling literature.

Because our focus is on the long term, we concentrate on the use of cyclic schedules in the production planning phase. Typically, production reservations are made before exact demands are known and are left unchanged for considerable periods of time. Frequently, reservations are made for families of similar items, leaving the detailed schedule (timing and sequence of individual items within a family) up to local decision makers. Scheduling in such a system reduces to a two stage
procedure. In the first stage, work is assigned to one of the reserved time intervals. In the second stage the sequence of assigned work is specified. A commonly used procedure is to assign jobs to the first reservation period with available capacity and to sequence the jobs within a period in arrival order or to take advantage of setup economies.

The purpose of this paper is to document the fact that cyclic planning is applicable in many environments and has the potential to simplify production management, to increase the efficiency of manufacturing and improve customer service. The method is particularly attractive because it is relatively easy to implement. We argue qualitatively that significant benefits result from easier scheduling, improved material handling and material flow, shorter production leadtimes, reduced planning and control costs, decreased safety stock buffer inventories, easier order booking and other improvements, and illustrate this with several real world examples. In addition, a simulation demonstrates that cyclic planning can have important advantages in a job shop environment.

We show that cyclic planning generates benefits by choosing reservations that coordinate flows. Dedicating processes to specific products enables more accurate capacity forecasts than with heterogeneous job assignment. Therefore, cyclic planning allows more accurate capacity and resource planning. This allows reduction of flow time and the flow time variability. The benefits are lower work in process inventories, decreased safety stock, and increased customer responsiveness. Delivery reliability may also be improved.

Also, cyclic plans have low information costs to customers and low control costs to the producers. Workers and managers know what work will be done during each time in the future. This knowledge helps each element of the production system plan its resources and its tasks at future times, insuring that actual production will be accomplished and completed on time. Customers' information costs are reduced because order booking is simple: the firm books an order into the first cycle for which capacity is available. Delivery dates are reliable and predictable within the plan, so that customers know when production will be delivered. Customer service improves.

Customer service aspects of cyclic planning are important in manufacturing and services. Many services employ cyclic plans because of low customer information costs and low provider control costs. Scheduled transportation services are one example. In this industry, information and control costs are very important: customers can reliably plan departure and arrival times, and the carrier can effectively utilize vehicles and reliably forecast capacity. In a similar way, cyclic plans allow service oriented manufacturing firms to provide products in forecastable and reliable manner. It may be possible to post the production plan so that customers know when orders can be executed and completed.
0.1 Literature Review

The cyclic scheduling literature studies the detailed scheduling of one or more work centers, i.e., establishing exact start and finish times for the production of individual items on machines. The objective is to minimize total costs consisting of inventory holding costs and setup costs (sometimes sequence dependent); sometimes positive setup times are assumed as well. It is typically assumed that demand is known and constant, and is met by establishing a cyclic schedule for all steps in the production process. Most of this literature involves scheduling on one machine. Thus the focus is on minimizing cost and not like the literature on modern manufacturing on creating flows. Recent work on single stage cyclic scheduling includes Rosenblatt and Finger [1983], Roundy [1985], Dobson [1987], [1988], Gallego and Roundy [1988], Jones and Inman [1989], Gallego [1989], and Matsuo et al.[1991]. Karmarkar and Schrage [1985] and Campbell and Mabert [1991] investigate the cyclic scheduling approach in the context of dynamic (deterministic but time-varying) demand. Cyclic scheduling has also been extensively analyzed for multi-stage systems with deterministic demand, see e.g. Crowston et al. [1973], Maxwell and Muckstadt [1985], McClain and Trigeiro [1985], Roundy [1986], and Jackson et al. [1988]. Maxwell et al. [1986] use cyclic schedules to investigate the interaction between product/process design and scheduling in a group technology setting. Graves et al. [1983] develop cyclic schedules for a flow shop where a job may return several times to any machine.

The literature on cyclic production planning in the sense in which we use the term is much smaller. Eriksson [1980] argues that it is difficult to predict production leadtime unless a cyclic plan is used. Hall [1988] advocates the use of cyclic planning and scheduling to improve coordination and provide opportunity for improvement. He argues that repetition of activities in a cyclic schedule enhances learning. He points out that engineering change orders can be easily coordinated under cyclic plans. He suggests that sequential stages be tightly coordinated using a cyclic schedule to get the benefits of a just-in-time system.

Whybark [1984] describes a cyclic production planning system (referred to as a "periodic system") at the Kumera Oy Company in Finland which produces power transmissions. The reported benefits are: decreased WIP, faster and on time deliveries, increased profits, and fewer production schedulers and expeditors. An important benefit of the system was a change in customer behavior: customers recognized that Kumera Oy's delivery dates were reliable and customers changed their ordering patterns to correspond to the company's schedules.
The organization of the remainder of this paper is as follows. Section 1 describes uses of the cyclic production schedules, and its cost and benefits. Section 2 presents the results of a simulation experiment which demonstrates some of the benefits described in the first section. Sections 3 and 4 describe two case studies of firms using cyclic planning and scheduling. Conclusions and suggestions for further research are given in section 5.

Section 1 Cyclic Planning

The concept of cyclic planning was developed in the early 1950's in Sweden as a planning methodology in a batch processing environment. In the sixties and seventies it was adopted on a large scale in Scandinavia, especially in Sweden and particularly by Volvo, see, for example, Eriksson [1980] and Eriksson and Lund [1983]. Recognizing that more than seventy percent of American and European manufacturing is organized as batch processing, the method may be relevant to many manufacturing environments. The authors know of several industrial companies in the USA and Scandinavia currently using cyclic planning and scheduling. As examples, many steel works run in a cyclic manner and two detailed case studies are found in Sections 3 and 4.

The cyclic planning/scheduling methodology is used in many areas outside of manufacturing; in the service industry the focus is often on assigning capacity to customer demands (work), e.g. airplane and train "schedules" can be viewed as cyclic plans, and manpower schedules are most often set in a cyclic manner, e.g. Baker [1976] describes personnel assignment using cyclic schedules.

Figure 1 shows a Gantt chart and a simple cyclic plan. The Gantt chart shows three stations and three job classes. All jobs follow the same station sequence, S1, S2 and S3. Production batches are split: the first product begins S2 before operation S1 is complete, similarly operation S3 begin before operation S2 is complete. Note that in this cyclic plan some capacity is unallocated to job classes to handle contingencies.
Figure 1: A Simple Cyclic Plan.

In this example, production time is temporally dedicated to different job classes at specified times. The use of different job classification schemes is discussed in Section 1.4. We refer to related parts assigned to a common production time period as a "product family". A product family may be defined on the basis of a related set of parts or on the end user.

1.1 Uses of Cyclic Planning

Cyclic planning can be used at different levels of aggregation by dedicating facilities to the production of specific products or product families during specified times. Planning of this sort can be employed for an entire manufacturing facility, a department within the facility, or a work cell within a department.

An example of the use of cyclic planning for an entire factory is readily given. Suppose that all jobs go through five activities: order accumulation, job preparation, production, assembly and test, and shipping. A cyclic aggregate plan can be established, as shown in Figure 2. Under this aggregate plan, orders received in week 1 are prepared for production in week 2, fabricated in weeks 3 and 4, assembled in week 4 and 5, and shipped in weeks 5 and 6. Likewise, orders received in week 2 are prepared in week 3, and the rest of the schedule follows similarly with a one week offset. The cyclic plan will be feasible if the flow times for each activity correspond to the assumptions of the schedule. The aggregate cyclic plan is capacity and activity oriented and ignores specific job details. Cyclic planning serves as an organizational integration tool and is a mutual agreement on key deadlines, that is, an agreement as to when components will be ready for assembly, shipping, and other departments.
At a lower level of aggregation, a production plan that corresponds to the aggregate plan may again be set using the cyclic planning method, or some other methodology, such as MRP may be employed.

1.2 Advantages and Disadvantages of Cyclic Production Planning and Scheduling

Cyclic production planning has several important benefits associated with reductions in cost and improvement in lead times, specifically order and production lead times. Order lead time is defined as the flow time for a job from the time of order taking until the completion of the last required operation. Production lead time is the flow time from the start of the first operation until completion of the last operation. Order lead time is an important measure of customer satisfaction because it measures how long a customer must wait from the initial request to the last operation.

The potential advantages of cyclic planning over other production planning/scheduling methods are:

1. Reduced complexity of the detailed scheduling problem.
2. Reduced time and cost of material handling; reduced set-up time and cost.
3. Reduced expected order and production leadtimes; reduced variance of order and production leadtimes.
4. Reduced planning costs and reduced control costs.
5. Reduced safety stock buffer inventories between departments.
6. Ease of booking orders into the production schedule.

7. Enhanced opportunities for learning and continuous improvement.

8. Indirect benefits to customers.

We discuss each advantage in turn. First, finding a good detailed schedule is a very difficult task, particularly in dynamic environments where parts mix and volumes are stochastic. Cyclic planning reduces the complexity of the scheduling problem by partially fixing the schedule so that each parts family can be scheduled independently. As the plan is used repeatedly, investment can be made in identifying detailed schedules that minimize production lead time and setup cost. Sequencing of production has been recognized as having an important effect on lead time. E.g. Eriksson (1980) gives an example of a four machine, four product flow shop with deterministic arrivals and processing times using cyclic planning, see Figure 3: the production lead time is 31% less in case 6 than in case 1. Sequencing has also been recognized as having substantial impact on setup and holding cost. Minimizing setup and holding cost is a commonly used objective in sequencing and cyclic scheduling models in the literature. The overall effect is reduced lead time, setup time and setup cost due to better schedules.

<table>
<thead>
<tr>
<th>Product Sequence</th>
<th>Case Number</th>
<th>Production leadtime in time units from starting station S1 to finishing station S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1P2P3P4</td>
<td>1</td>
<td>P1  P2  P3  P4  Total</td>
</tr>
<tr>
<td></td>
<td>S1 S2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S3 S4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 10 10 13 46</td>
<td></td>
</tr>
<tr>
<td>P1P2P4P3</td>
<td>2</td>
<td>P1  P2  P3  P4  Total</td>
</tr>
<tr>
<td></td>
<td>S1 S2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S3 S4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 7 10 10 37</td>
<td></td>
</tr>
<tr>
<td>P1P3P2P4</td>
<td>3</td>
<td>P1  P2  P3  P4  Total</td>
</tr>
<tr>
<td></td>
<td>S1 S2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>S3 S4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 7 7 10 34</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Shortest Total Production Lead Time for 6 Cyclic Product Sequences Involving 4 Products on 4 Machines (Adapted from Eriksson [1980], p. 68).

The second benefit occurs because cyclic planning creates temporal flow lines. In this aspect, cyclic planning is similar to group technology, which creates a flow line in a batch environment by producing related parts on a dedicated line. Advantages of group technology are: easier process planning, better scheduling and more efficient material handling. Closer coordination between machines becomes possible, allowing overlapping production by machines in sequence. Smaller transfer batches may be possible, reducing production leadtime. These advantages accrue because reduced heterogeneity of parts allows standardized tooling, shorter setup times and lower set-up costs. The physical organization of a group cell allows shorter moves and more coordination between stages within the cell.

Like group technology, cyclic planning attempts to create flow lines in a batch environment, by producing related products on temporally dedicated machines. The items produced in the same portion of the cycle follow the same flow path. Most advantages of group technology listed in the last paragraph are potentially available in cyclic planning. This results in more efficient use of resources, reduced costs and shorter order and production lead times.

The third benefit occurs because the production environment is less stochastic. In cyclic planning, relatively homogeneous work is assigned to servers during production buckets. This makes it is easier to measure production capacity and to insure that available capacity is adequate. Also, simultaneously required resources can be more reliably coordinated because there is limited opportunity for errors as the schedule is easily understood and repeats. It is particularly important
to note that production will not be delayed by the failure of needed parts to arrive. This is because the arrival of required upstream parts is coordinated by the cyclic plan. Better coordination reduces queueing delays and production (and order) leadtime. The variance of production leadtimes will also decline because the environment is less stochastic. In operational terms these advantages translate into reliable schedules, more effective use of scheduled resources, less need for safety stock buffer stocks and lower work in process inventories.

Fourth, planning costs are lower because of the simplicity of the repeated plan. Information about the actual production plan is very visible. The advantages of visibility are similar to those in a "just-in-time system". Failure to transfer parts on schedule or of correct quality or quantity is very apparent. The source of the failure is clear because the schedule is simple. Thus, some of the control related advantages of the just-in-time system are achieved.

Fifth, coordination between the area using cyclic planning and upstream and downstream departments is easier. Coordination with upstream departments is easier because the area's requirements are more predictable and less variable in each cycle. Smaller safety stock buffer inventories between the area and upstream departments are therefore required. Downstream departments benefit as well as there is greater certainty of transfers in timing and quantity from the area using cyclic schedules. Thus, safety stock buffer inventories between the area and downstream departments can decline.

Sixth, in a cyclic planning environment, available production capacity is easy to compute. This is because production flow is the same for all products in the same family. There is no contention for resources with other families. If processing rates are known for each part in the family, and total setup time is predictable, capacity estimates can readily be made. Marketing and other downstream departments can more easily plan orders and set delivery dates. The simplicity of cyclic planning enables downstream stages to make production orders and to forecast order leadtimes that are accurate.

Seventh, there are enhanced opportunities for learning and continuous improvements using cyclic planning because the plan is simple and it repeats. Repetition makes problems observable and increases the payoff from improvements. The effects of local decisions on the entire flow are easier to establish because the cyclic planning system makes the interrelationship of production steps clear. To give two examples, the effects of set-up time on system performance are readily identifiable, and the causes of idle time of equipment are easier to assign. Transparency of interrelationships and ease of detection of problems enables continuous improvement. In this
respect, cyclic planning is very compatible with the continuous improvement approach associated with the just-in-time philosophy.

Eighth, there are important indirect benefits due to customers’ reactions to the system. Customers or downstream units of the firm recognize that delivery schedules are reliable under cyclic planning. They change ordering policy to match the cyclic plan, reducing order leadtimes further. When order lead times are short and predictable, customers will place fewer speculative orders and request fewer changes in specifications and due dates on existing orders. The company is thus provided with more accurate knowledge of actual demand, and can avoid costly rework, expediting and rescheduling. As documented in the case study in Section 4, customers may do their own scheduling within the cyclic plan. This allows customers to use production resources according to their most highly valued use.

All these advantages occur in job shops and flow shops. This is particularly important to note, because the cyclic scheduling literature has only studied flow shops. The example in Section 2 demonstrates cyclic planning in an idealized job shop. The first case study in Section 3 reports the effect of cyclic planning in a job shop, and the second case study in Section 4 reports the use of cyclic planning in a flow shop. Note that the value of cyclic planning depends on the particular environment in which it is used. For example, in job shops having complicated parts flows or in assembly operations, cyclic planning may reduce queueing delays due to part coordination problems more than in flow shops. On the other hand cyclic planning may be more difficult to implement in job shops with frequently changing mix and volumes. The differential value of cyclic planning in different production environments is an important research question.

Partially offsetting these potential advantages are two disadvantages. First, in cyclic planning resources are dedicated to parts families according to a rigid schedule. If there is not enough work within a part family to keep a resource fully utilized, production capacity is lost. This introduces delays for other families that could be reduced in more flexible planning systems.

Second, orders must wait for the beginning of an available cycle to begin production: with cyclic planning queues develop in front of the first machine, adding to the order leadtime, but not to the production lead time. Cyclic planning has a built in wait time until the start of a production cycle that has available capacity. If demand is highly variable and the system near capacity, demand surges cause orders to wait for several cycles. Hence even though under cyclic planning production leadtimes can be short and have low variance, order leadtimes can be long and have high variance under unfavorable conditions. Note, however, that even when leadtimes are highly variable, once an order is received, its order leadtime is highly predictable.
1.3 Variations of the Cyclic Planning Method

The cyclic production method assigns blocks of processing time to product families so as to create a flow of products. How the product families are defined depends on the application. For example, part families may be made up of sets of related parts, or product families may be made up of varied parts belonging to a single customer. We will refer to the first type of cyclic plan as a "product" oriented plan and the latter as a "customer" oriented plan. For example, a customer oriented cyclic plan can be used to plan production for a fabrication department supplying parts to many assembly divisions of the same firm, by temporally dedicating capacity to divisions (the customers of this application).

The advantage of the product oriented system is that more homogeneous work is scheduled in each part of the cycle, reducing control costs, setup costs and leadtimes. However, the customer oriented cyclic planning system allows each user to do its own scheduling and to set priorities for its orders according to their value. This can add considerable value to the firm. Self scheduling avoids a priority system administered by a central production planning department that forces tradeoffs between customer's priorities. Centrally administered priority systems based on prices can work but may be difficult to administer. As an example, it may be difficult to establish the cost and benefits of different levels of service, and therefore, difficult to determine the correct prices. This is especially true in environments where costs and benefits change frequently.

Cyclic planning systems can be designed to mix customer and product orientation. For part of a production period, customer oriented cyclic plans are used for a restricted subset of each user's products, and for the balance of the period, all users' work is jointly produced in a product oriented cyclic plan. See Figure 4 for an example of this type of application.

![Figure 4: An Example of a Mixed Product and Customer Oriented Cyclic Schedule.](image-url)
Section 2 presents a simulation of the use of a cyclic plan in a job shop. The example presents quantitative analysis of the benefits, especially those of reduced expected order and production lead times and reduced variance in order and production lead times.
Section 2  A Simulation Study of Cyclic Planning in a Job Shop

In this section we report on a simulation study of a job shop. We demonstrate that cyclic planning provides a means of coordinating product flows through the shop that has the potential to significantly reduce order and production lead times. Although the example is very simplistic it highlights why cyclic planning may be particularly attractive in job shops, where it may be hard or impossible to reorganize the facility into physical flow lines. This contrasts with the existing literature on cyclic scheduling that has focused on one machine and flow shop environments.

![Diagram of Job Shop Layout and Job Flows]

Figure 5: Square Job Shop Layout and Job Flows.

In this example we consider a highly stylized job shop with \( n^2 \) machines and \( 2n \) job classes. The machines are laid out in a square with \( n \) machines to a side, see Figure 5. Each job needs to be processed by \( n \) machines in a straight line, either from left to right or from top to bottom in Figure 5, and the job classes correspond to the \((2n)\) straight line paths through the job shop from left to right and from top to bottom. The numbering scheme for machines and jobs is also indicated in Figure 5. All processing times are deterministically equal to 1 time unit. It is assumed that set-up time is zero and set-up costs are negligible. For each job class, jobs arrive according to
a Poisson process with rate $\lambda$. Since each machine works on exactly 2 classes of jobs, the long run average machine utilization is $\rho = 2\lambda$ ($\mu = 1$) for each machine, and we will assume that $\lambda < 0.5$.

We compare two scheduling approaches for the square job shop. The first approach utilizes first come first served (FCFS) at each machine. The idea is that a scheduling system, such as MRP, schedules work at each machine based on order releases at that machine. Once a job order arrives, it is scheduled into the first available slot at the first machine it must use. The schedule at the next machine in the routing is based upon the first available time at that machine once work on the first machine is complete.

Using this scheduling approach the distribution of relevant performance characteristics for crossing jobs $i^*$ and $*i$ are the same for $i = 1, ..., n$. (See Figure 5 for a diagram that shows the crossing job flows.) It is important to note that performance characteristics for jobs of types $i^*$ and $j^*$ ($i \neq j$) are different. For example, in an $n \times n$ shop with FCFS, classes $*1$ and $1^*$ have longer production lead times than classes $*n$ and $n^*$. Classes $*1$ and $1^*$ have to contend with newly arriving jobs at each stage, while classes $*n$ and $n^*$ contend with jobs that are about to leave the system. Since all service times are deterministic, the variability of the interarrival times of jobs at the last machine they visit is significantly less than that for newly arriving jobs. Hence $*1$ and $1^*$ experience a more variable stream of contending arrivals and thus experience longer queueing delays on average. Hence the shop needs to be simulated in its entirety in order to understand FCFS performance.

The second approach uses the cyclic planning (CP) approach as follows. The cycle length is $T$ time units, and machine $(i,j)$ alternates between spending $T/2$ time units on jobs of class $i^*$ and spending $T/2$ time units on jobs of class $*j$. We assume transportation times are zero, so that a job can start the next operation as soon as it has completed the current operation. The reservation periods for individual machines in the path of each job class are offset by one time unit (which equals the processing time of a job) so that a job only waits in front of the first machine it visits. In our stylized square job shop, this is always possible. In the cyclic plan jobs of a given type will be processed in the order in which they arrive. A job will not start processing on its first machine unless it can be completed without interruption. Figure 6 presents a Gantt chart that gives the cyclic plan for a 9 (=3 by 3) machine shop with $T = 10$. An MRP system can be used to schedule jobs using CP: when a job arrives, it is scheduled into the first available cycle at the first machine and all other downstream machines. Using CP, the job's production schedule is known as soon as it arrives, in contrast to schedule uncertainty using FCFS.
Note that the entire cyclic plan for the shop is determined by the single parameter T. Under CP, each job type is treated in an identical manner and there is no interference between job types. Therefore performance characteristics for the entire job shop can be obtained by simulating only a single job type. The cyclic plan guarantees that the time elapsed between the start of processing of a job and the completion of a job is always equal to the job's total processing time. In other words, CP keeps WIP at an absolute minimum. The net effect is that in simulating CP for the square job shop we only need to keep track of the waiting time of a job up to the start of processing on the first machine, regardless of the size of the job shop. Admittedly, in the square job shop with deterministic unit processing times it is easy to come up with a cyclic plan that is extremely efficient. In real world job shops, coming up with a good cyclic plan (i.e. one that minimizes WIP) represents an important optimization problem.

It can be noted that assumption of zero set-up times and costs favors the performance of FCFS over CP. Some batching does occur under CP since similar jobs are processed on machines during reserved times, but there is no batching for FCFS. Therefore, set-up cost and leadtime efficiencies potentially generated by CP's batching policy are ignored. If FCFS was compared to CP in an environment with set-up times or costs, FCFS would perform worse relative to CP. Thus the experiment is designed, in some sense, to favor FCFS.

The FCFS shops were simulated using the SIMAN simulation package on a personal computer. One run comprised about 20,000 jobs of each type, so the 8x8 shop required simulating about 3.2 million jobs. The cyclic plans were simulated using Think Pascal. Only two runs were needed, one for each value of λ, and we used T = 10 for both runs. Each run comprised 200,000 jobs.
To judge the performance of the two scheduling approaches, order leadtime (OLT) and production leadtime (PLT) are recorded for each job. We performed two sets of experiments, one with $\lambda = 0.4$ ($\rho = 0.8$), and one with $\lambda = 0.45$ ($\rho = 0.9$).

Figure 7 compares the average OLT for all job types under CP with OLT statistics under FCFS for $\lambda=0.4$. For FCFS the average OLT for all jobs is reported, as well as the OLTs for the best and worst job classes. Several points are worth discussing. For small shops (up to $3\times3$), every job class has a smaller average OLT under FCFS than under CP, while for large shops ($7\times7$ and up) the reverse is true. In addition, under CP the average OLT is identical for all job types, whereas significant differences exist between job classes under FCFS, particularly in the larger shops. As predicted above, in an $n\times n$ shop with FCFS, classes *1 and 1* are worst off, and classes *n* and n* are best off.

Figure 8 shows average OLT when $\lambda = 0.45$ ($\rho = 0.9$). A comparison with Figure 7 shows that with higher utilization CP outperforms FCFS on an average job in a $4\times4$ or larger shop. From the point of view of minimizing OLT, CP becomes relatively more attractive when the size and utilization of the shop increase.
Figures 9 and 10 report average PLT's under CP and FCFS for $\lambda = 0.4$ and $\lambda = 0.45$ respectively. The attractiveness of CP is more pronounced, even for very small shops. It is worth pointing out here that PLT and WIP inventory are proportional. For any size shop larger than 1x1 CP is superior to FCFS with respect to PLT and WIP. This is because under CP the PLT is equal to the sum of the processing times and no waiting occurs.

Figures 11 and 12 shows the standard deviations of the OLTs for FCFS and CP. The attractiveness of CP over FCFS with respect to the standard deviation of OLT increases with machine utilization and shop size. For small shops, the standard deviation of OLTs under CP is larger than under FCFS. However, it should be remembered that under CP once an order arrives, its OLT is known with certainty. On the other hand, the OLT under FCFS can be influenced by later arrivals from other classes and is thus still uncertain.

In Section 1.2, the advantages and disadvantages of cyclic planning were described. The above example demonstrates that cyclic planning can reduce the average order and production lead time and the variance of these leadtimes compared to FCFS in a job shop. However, the example only captures the third advantage which was reduced queueing delays due to better coordination of jobs. The other seven potential advantages are unmeasured in the example. Some are more relevant than others. For example, scheduling issues such as sequencing and setups have no impact in this example, so that the first advantage is not significant. However, better material handling (the second advantage) seems likely. The fourth advantage does not seem important because FCFS has minimal planning and control costs. Reduced buffer inventories (the fifth advantage) and ease of booking orders (the sixth advantage) could all be significant advantages of cyclic planning compared with FCFS. The cyclic schedule may introduce learning opportunities in our hypothetical job shop, so that the seventh advantage may be likely. Under cyclic plans, customers will know with certainty when orders will arrive once they are booked into the schedule, so that indirect benefits to them are possible.

Finally we note that the square job shop we simulated allows for easy to construct and very efficient cyclic plans. Finding good cyclic plans in a real life job shop is likely to be a non-trivial undertaking. For specific job shops, FCFS may out perform cyclic planning when the disadvantages noted in Section 1.2 become important.

The following two sections presents case studies observed by the authors that involve the use of cyclic planning in manufacturing environments.
Figure 7: Average OLT as a Function of Shop Size when $\lambda = 0.4$.

Figure 8: Average OLT as a Function of Shop Size when $\lambda = 0.45$. 
Figure 9: Average PLT as a Function of Shop Size when $\lambda = 0.4$.

Figure 10: Average PLT as a Function of Shop Size when $\lambda = 0.45$. 
Figure 11: Standard Deviation of OLT as a Function of Shop Size when $\lambda = 0.4$.

Figure 12: Standard Deviation of OLT as a Function of Shop Size when $\lambda = 0.45$. 
Section 3  Cyclic Schedules at a Drill Bit Manufacturer

This case study describes a Danish company that produced and sold a broad line of drill bits. In total, it produced more than 8 million units per year in batch sizes ranging from a few to several thousand. The company used a wide range of production technologies, from conventional machine tools to dedicated highly automated equipment. Manufacturing involved about 10 different processes (e.g. cutting, grinding, turning, milling, stamping, soldering, hardening, surfacing, and packing). Production equipment was organized primarily in a product oriented lay-out.

In the recent past, the company reorganized its production system. Many issues were considered in the reorganization. The wage system, layout, production organization, technology, and production control methods were changed. These changes are described in detail in Johansen [1990]

One of the changes was the introduction of a cyclic planning and scheduling system. Cyclic planning was adopted for two reasons. First, an analysis showed that set-up time depended primarily on drill bit diameter and secondarily on drill length. Production cycles based on diameters therefore minimized set-up time. Second, cyclic planning supported efforts to decentralize shop floor control and to integrate production and sales.

Figure 13 outlines the cyclic planning method used. The cycle period equaled 4 weeks (20 working days) and each product family was produced once each cycle. The cyclic plan was time and capacity oriented, and showed the start and finish times for each family plus available capacity. For each family, capacity was based on a common unit of the bottleneck resource in the production group.

![Cyclic Schedule Diagram]

Figure 13: The Cyclic Schedule For The Drill Manufacturer
The plan had a rolling horizon of 3 cycles. The reservation periods in the first cycle were fixed and could not be changed. The time reservations in the second and the third cycles were permitted to change within predetermined levels (e.g. within 5-10%). Long-term planning was based upon actual customer orders and sales forecasts.

The sales function directly booked customer and inventory orders into the cyclic plan using capacity estimates. The sales function was allowed to book new orders into the cyclic plan until one week before production of a family, as long as capacity was available. Figure 14 summarizes the procedure used to start production.

The changes in layout, organization, production technology and production control enhanced performance. Production leadtime was reduced by a factor of 7-8, labor productivity increased by 60%, on time delivery increased from below 40% to almost 100%.

Many changes were made to the system in the reorganization. However, the concept of cyclic planning served to integrate production and sales by a mutual agreement of how to carry out production on a daily basis, and was a major reason for the dramatic rise in delivery performance.
1. One week before start of production of a family the planning department "freezes" the schedule.

2. Central planning schedules production of packing materials.

3. Production documents are prepared. Each product had its own documents identifying type, name, diameter surface, and other specifications. The central production control department hands over production papers to the foreman the day before start of production. Detailed scheduling for the production group is done by the workers themselves.

4. Production is visually monitored by the foreman. If large delays or machine breakdowns occur, the foreman informs the central planning department and/or the production manager. They decide on further actions such as overtime or delaying orders.

Figure 14: Steps Used to Start Production at the Drill Bit Manufacturer.
Section 4  A Customer Oriented Cyclic Plan in a Prototype Department

The second case study involves a service department for a large U.S. multiple division firm, that produces prototype products for the divisions. Because of the competitiveness of this market, we omit the company name or its industry. Suffice it to say that the basic product class is an internationally known consumer product. Prototypes are design experiments of new products or variations of existing ones. Orders for prototypes, along with specifications are delivered by customers to the department. When the results of testing the prototype are complete, customers often request additional prototypes. Production of prototypes takes place in a ten stage flow process with a single bottleneck operation in the fifth stage. Processing times at each stage are predictable, although jobs were of greatly varying size. Because of concerns for quality, a job at any stage needs to be scheduled for completion during a single shift.

Before the introduction of the cyclic planning system, scheduling of all orders was done on a first come-first served basis, with schedules set by the bottleneck operations and the one shift completion constraint. Slack time was built into the schedule at early stages to insure that necessary materials were available.

Divisions placing orders were generally not informed of delivery dates at the time of order, since schedules depended on the mix of jobs. Customers' priorities were informally communicated with the scheduler who considered them when possible. Work loads varied daily and seasonally and caused order lead times to vary in ways unpredictable to the customer.

Faced by competition, the firm re-examined its operations, especially its ability to improve existing products and to develop new products. During this re-examination, the prototype department's objectives were changed. Previously, cost and quality were the primary concerns to department management. After the changes, reducing order leadtime became an important objective as well.

Few changes were made to the physical process. However, a customer oriented cyclic production planning system was introduced. Under this system, production time in the morning is dedicated to work for the largest two customers. During this period, specific time was dedicated to each customer on each machine to create a flow with no queueing delays. Jobs run during this period were restricted to jobs with short processing time at the bottleneck operation. In some sense, the two large customers "owned" the morning production time: they paid a charge to have
exclusive control of this production time and they could trade production time with other customers.

A very important change was that with the new system, the two large customers did their own scheduling. This enabled them to make their own priority tradeoffs and to know exactly when the orders would be completed. During the afternoon and the second shift all other jobs are run using an improved version of the old system.

The changes in the scheduling system had a very favorable effect on system performance for all customers. It is interesting to note that most of the positive effects resulted from the interaction of the new scheduling system with customer demand. We note four important changes induced by the new system. First, the ability of the two large customers to set their own priorities enabled them to use the prototype facility to their own highest valued use. Second, order and production leadtimes declined for the largest two customers for work scheduled in the mornings. Because the types of jobs that were run in the mornings were predictable, necessary materials could be inventoried, eliminating the safety time previously scheduled. Leadtimes for morning jobs were also shortened because the schedule allowed jobs to flow without wait between machines. The result was that the two large customers had reduced order and production leadtime on their morning jobs. Third, with short production leadtimes and low variance in production leadtimes these customers actually submitted fewer jobs. Instead of submitting parallel prototypes, these customers waited to see results from initial experiments, which would now arrive sooner and more predictably. This reduced the load on the morning schedule, reducing order lead times. Fourth, the larger customers redesigned some work that was previously run in the afternoon or evening so that it could be run during the mornings, reducing loads in the afternoon and evening. The net effect was that order and production lead times actually decreased for all customers, speeding up new product development while reducing cost to the firm.
5 Summary and Conclusions

This paper has presented a definition of cyclic planning and described its uses. Some potential advantages and disadvantages of the method were explained. A simulation experiment demonstrated the potential of cyclic planning to coordinate activities within a job shop and to reduce the average production and order lead times. Two case studies considered details of cyclic planning applications.

Many important issues about cyclic planning remain to be explored. Detailed design issues about the cyclic plan itself need study. For example, the choice of the cycle time, how to partition production time for each productive resource within each cycle, and the assignment of products to product families are detailed design issues that need to be considered to create an efficient cyclic planning system. The performance of a cyclic plan depends on the detailed scheduling method employed, and more needs to be known about this interaction.

There are also many interactions between the production system and cyclic planning that require further investigation. Production system capacity, system balance and equipment flexibility have an important affect on the performance of any cyclic plan. Understanding these interactions is important to predict how well the system will function.
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