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Design of a period batch control planning system for cellular manufacturing

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Chapter 4 Design factors for basic unicycle PBC systems

This chapter discusses the main factors that have to be taken into account when designing a basic unicycle period batch control system. Section § 4.1 will show that designing a planning system cannot be isolated from designing a production system. We will therefore examine the mutual relationship between PBC system design choices and production system design.

For the design of a basic unicycle PBC system, the length of period is an important design factor. Section § 4.2 focuses on the determination of this period length P in a PBC system. The relationship to the production structure is explored and factors that have to be taken into account when determining the period length are distinguished.

Stage definition is the other important design factor for PBC systems. Stage definition consists of two separate decisions: setting the number of stages N, and determining the contents of the stages. They will be discussed in the next two sections.

Section § 4.3 discusses the number of stages N. We examine the relationship between the structure of the production system and the decomposition of the planning system into N stages. This helps us to identify aspects that affect the decision about this number of stages.

Section § 4.4 elaborates upon the contents of the stages. It discusses the relationship between cells (WHERE operations are being performed) and stages (WHEN operations are being performed). We will provide a mathematical model to offer guidance on deciding how to appropriately allocate operations to the stages.

The chapter ends with Section § 4.5, which provides a summary and conclusions. At the end of this chapter, the first part of the third research question will have been answered, i.e., we will have shown what choices have to made when designing a basic unicycle period batch control system for co-ordination between cells.

§ 4.1 Concurrent design of production system and planning system

A production system consists of various elements: machines, operators, tools, and handling equipment. These elements are organized in such a way that the system can transform input (material) into desired output (products) within a period of time. The structure of a production system is determined by both the characteristics and the organization of the elements of the system. This includes the layout in the factory, the organization of the material flow through the factory, and the allocation of tasks to operators.

A production system is co-ordinated using a planning system. This planning system prepares the decisions with respect to the utilization of the production system over time in order to achieve the required performance with respect to speed, dependability, flexibility, quality, and costs. Information is the input for the planning system. Planners, computers, and other information bearers are elements of the planning system. The various tasks that are performed by these elements of the planning system are organized in such a way that the system is able to obtain the desired output (a plan) to fulfil the higher-level system objectives. The structure of the planning system is determined by the characteristics and organization of these elements. More specifically, the planning system structure shows what planning tasks when, where, and by whom will be performed. The planning system decides what to make when and where in the production system.

§ 4.1.1 Relationship between production systems and planning systems

The design of a suitable structure for the production system and the design of the structure of the planning system are interrelated. This relationship is often considered unidirectional, e.g., first determine the production system structure and then the planning system structure can be deduced. Figure 4.1 shows this traditional unidirectional conception of a design process.

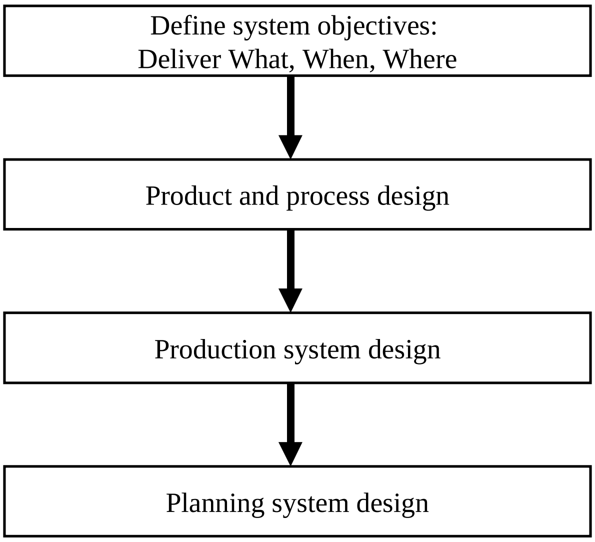

Figure 4.1 Traditional sequence design process

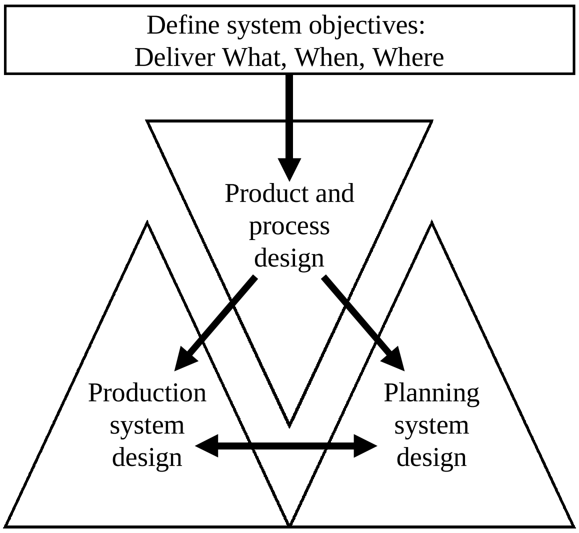

Figure 4.2 Mutual interaction between design of production and planning system

Although this sequence is often applied, we should not consider the relationship between production and planning system design to be unidirectional. To understand this relationship, we should take into account the origin of the data used to determine the structure of both systems. This data originates from product and process design. We will clarify the role of this data in the design process by examining the interaction between both systems.

Figure 4.2 shows our view of the interaction between the design tasks. It includes all traditional relationships, but adds some important new relationships as well, especially with planning system design. The relationships within this figure will be discussed.

In order to design a system, we firstly have to identify the function of the system. This helps us to determine the activities that have to be performed in both the production and the planning system. We can specify the function of the system in terms of *what* to produce *when* and *where,* i.e., in terms of the system objective. This strategic decision sets several objectives for the planning system, i.e., logistical parameters such as lead time, volume, flexibility. For decisions on these parameters, knowledge is used about the market (opportunities and treats) as well as some elementary characteristics of the production system and planning system (strengths and weaknesses). This results in a basic structure for the logistical system, as it decides on the customer order lead time, which has consequences for the location of the customer order decoupling points, production units, outsourcing decisions, and so on.

Before we can determine in more detail the elements required in the production system, we first have to decide about product design and process specification. These decisions determine the processing functions that will be required in the transformation process, as well as the relationship between these processes (the sequence).

There is often a direct relationship between the specified functions and the available elements in the production system. In these cases, the decisions about product and process design result in direct relationships between elements in the production system, which subsequently influence the structure of the planning system. If elements in the production system are selected that, for example, will bring uncertainty of yield for this operation, the design of the planning system may have to compensate for the negative impact of this uncertainty on the overall system performance. This might lead to the insertion of more buffer capacity between the operations. The traditional direction of interaction from the design of the production system to planning system design will therefore be in force.

However, it should also be observed that a link from planning system design to production system design might be present. The selection of processes and their sequence within product and process design may have direct consequences for the structure of the planning system, which subsequently influences the design of the production system. The system objectives may necessitate that the planning system have a specific structure, which might have consequences for the design of the production system as well.

For example, suppose a processing sequence is specified that involves many different processes and the system objectives require both a high utilization of a bottleneck resource and short throughput times. These objectives can be realized only through an appropriate design for the planning system. Subsequently, this imposes constraints on the design of the production system with respect to a lay-out that enhances the quick transfer of items between successive processes.

The design of the planning system may also require that specified processing steps necessary to perform the transformation be subcontracted or outsourced, although elements of the production system might be able to perform the operations.

After the process planning has been finished, the next important step in determining the planning structure is to configure the planning bill of materials. This configuration matches processing steps with work orders. The specification of work orders is a decision about the planning system structure, as it concerns the release of work to and hence the utilization of the production system. The configuration of the planning bill of materials influences the location of stock within the system. The production system ought to be able to accommodate the stock positions that result from the design of the planning system.

These three examples show that interaction from planning system design to production system design will also be in force.

If the traditional sequence of the design process is followed, the grouping of operations into work orders is based on data that originates from the structure of the production system, as its design precedes the planning system design. However, the structure that is being designed for the production system may not be the most appropriate structure for designing a planning structure. For example, if the process plan specifies a milling operation before a welding operation, the production system design might locate these activities and their equipment in separate functional departments because of the differences in technology. In order to achieve the required logistical performance, the planning system may prefer a different configuration of the production system. The product routing data includes information on the transfer times between two operations within the production system. If this information is based on a functional configuration of the production system, this may influence the grouping of processing steps into work orders. It can result in huge inefficiencies if the planning system releases such work orders very early, as this results in high throughput times.

We conclude that the relationship between the design of a suitable structure for the production system and the design of the structure for the planning system is not unidirectional. In mutual interaction between both systems, decisions should be taken on the material flow and the control of this flow, the subcontracting policy, the specification of work orders, and the allocation of buffers and stock locations in the system. This study considers the relationship between PBC planning system design and cellular organized production system design. We will determine the effect of various configurations of the PBC planning system on these decisions and their impact on production system design.

§ 4.1.2 Planning literature and production system structure

How does literature on the design of production systems and planning systems take this relationship between planning system design and production system design into account? We have to make a distinction between literature on the design of system structures and literature on the optimization of systems. Scheduling literature (e.g., Conway, Maxwell, & Miller, 1967, Baker, 1974, French, 1982, Rodammer & Preston White, 1988, Wein & Chevelier, 1992, Riezebos & Gaalman, 1998) does not take into account a possible redesign of either the production system or other parts of the planning system. It is directed towards finding a 'best' way to process certain jobs on one or more machines, but the number of machines or the routing of the products is not considered as a variable. The optimization oriented literature does not provide assistance in the design of the planning or production system.

Literature on the Kanban system (e.g., Sugimori, Kusunoki, Cho & Uchikawa, 1977, Mitra & Mitrani, 1990, Miltenburg & Wijngaard, 1991) generally assumes that the cell structure is fixed, that cells apply a type of line layout, and that the manufacturing processing and throughput times for the products within a cell are known (or at least some characteristics of their probability distributions). The design of the planning system is focussed on determining the number of Kanbans per product per cell (i.e., determining the total throughput time of a Kanban) as well as a level schedule of end products such that the loading of the various cells fluctuates minimally. Kanban literature does therefore take the structure of the production system for granted and designs a planning system without taking notice of the possibilities that are a consequence of the mutual relationship between both systems. More general literature on Just In Time system design (e.g., Schonberger, 1982, Monden, 1983, Hall, 1987) usually includes some general notes on production system redesign and planning system design. It describes some desired characteristics of the production system structure if it is to be controlled with a Kanban system. However, it does not offer adequate support for making congruent decisions on the structure of both systems .

The Optimized Production Technology (OPT) system (e.g., Fox, 1984, Goldratt, 1981) pays more attention to the structure of the production system when a planning system is being designed. The location of the bottleneck in the production system has to be determined before the planning of the rest of the system is undertaken. OPT even prefers specific elements of the production system as bottleneck. Bond (1993) notes that a machine as bottleneck is preferred instead of operators, tools, handling equipment, or buffer locations. The reason for this preference lies in the design of the planning system. The detailed planning and frequent replanning of OPT requires a high level of control of the planning system over the progress of work within the production system. A machine as bottleneck is more easily identifiable, more visible, and the rest of the system can more easily be oriented towards the progress of work on such a machine than in those cases where another element of the production system is the bottleneck. If the production system is modified such that a machine becomes the bottleneck, this can improve the whole system design.

The OPT framework prefers the location of the bottleneck in the chain of processes required to produce the products. This location is generally upstream of the production process, as this leads to less work in progress, smaller cycle times and smaller amplitudes in the waves of work flow. Goldratt (1981) states that '*the resources must be organized such that the bottleneck resource is used primarily at one of the earliest stages of the production process, and* <u>*not*</u> *near the end.*' OPT literature therefore recognizes the relationship between production system and planning system design. However, it places a strong emphasis on production capacity and material flow, while other elements of the production system and the organization of the production resources receive less attention for redesign. Finally, OPT can be used as a tool for simulating, analysing and optimizing production operations, which may help to improve material flows. This literature thus recognizes the mutual relationship between production system and planning system design.

In general, literature on planning frameworks such as MRP I and MRP II (Orlicky, 1975, Wight, 1984, Vollmann, Berry, & Whybark, 1997) is mainly concerned with the function and interaction of the various planning modules within the planning system and pays much less attention to the mutual relationship with the production system[1]. However, it is essential that the planning system uses a correct model of the production system. The structure and characteristics of the production system are used as input for the MRP planning process, for example in the design of the Bill of Material, Bill of Labour, and Bill of Capacity. Orlicky [1975: 207] notes: *'The Bill of material should reflect, through its level structure, the way material flows in and out of stock. The term "stock" in this connection does not necessarily mean a stockroom but rather a state of completion. … Material requirements planning also assumes that the bill of material accurately reflects the flow (in and out of stock). Thus the bill of material is expected to specify not only the composition of a product but also the process stages in that product's manufacture. … This is vital for mrp because it establishes, in conjunction with item lead times, the precise timing of requirements, order releases, and order priorities'*. The benefits of an interaction between both design processes are not recognized in the literature on MRP system design.

Alternative planning frameworks have been developed by Bertrand, Wortmann & Wijngaard, 1990b, Bauer, Bowden, Browne, Duggan & Lyons, 1991, see also Browne, Harhen & Shivnan, 1996, and Banerjee, 1997. These frameworks pay more attention to the relationship to production system design. For example, in their Factory Co-ordination module, Bauer, Bowden, Browne, Duggan and Lyons (1991) make a distinction between a production system redesign task and a work flow co-ordination task.

Bertrand, Wortmann and Wijngaard (1990b) recognize the important role of co-ordination within and between production units and the sales department in structuring the planning system. They also consider the consequences for the production system. They define a production unit mainly from a production control point of view. The operations that are to be performed within a production unit belong to the same production phase. They design a suitable overall control structure for the goods flow between these phases. A production unit should be able to reach its (logistical) objectives and to perform its operations independent of other production units as long as material and capacity is available.

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[1] It is remarkable that the characteristics of the production systems to which the initial publications on MRP refer have much in common with the production systems that are being redesigned if PBC systems are implemented. They both have component production as well as assembly operations.

The production system need not be decomposed according to these units, even though the planning system is. In Wortmann, Muntslag & Timmermans [1997: 169], Muntslag even notes that it would generally be undesirable to create separate production departments for each production phase, i.e. to let the decomposition of the planning system into production units be identical to the decomposition of the production system into production departments. The reason for this incongruence is the fear of a lower utilization of resources. In their design for a planning system structure for goods flow control, Wortmann, Muntslag & Timmermans [1997: 167] present some criteria for determining goods flow control items and production phases. They suggest decoupling the goods flow according to (1) the possibility of reducing uncertainty, (2) the presence of a resource capacity bottleneck, or (3) the product structure.

We conclude that the work of Bertrand, Wortmann, and Wijngaard and the related work of Muntslag take the characteristics of the production system into account when designing a planning system. However, the relationship between the concept of a production unit and the decomposition of the production system is not worked out in detail, and the main focus is still on the production control aspects.

From this literature review, we conclude that the mutual relationship between structuring the production system and the planning system is only partly recognized in literature on the design of planning systems.

§ 4.1.3 PBC literature on production and planning system design

In PBC literature, there is a strong emphasis on the mutual relationship between structuring the production system and the planning system. Burbidge [1975a: 79-80] gives an example of a plant that used a functional layout for its production system and successfully operated PBC with a cycle (period length) of four weeks. He found that if this firm had redesigned its production system by applying a group layout, a PBC cycle length of one week would have been possible, due to the use of other planning mechanisms for some critical components. This example shows a production system redesign enabling a planning system redesign.

The other direction of the relationship between both system structures is also recognized in this literature. The structuring of a PBC system can make it necessary to modify the production system, using for example the '*Production Flow Analysis technique to identify complex routes and eliminate them by re-routing, re-design, change of method, or buying instead of making*' [ibid. 1975a: 85].

According to Burbidge, the design of a production control system is strongly related to the design of the production system. In his initial work on planning, Burbidge (1962) gives two definitions of production control. In its widest sense, production control is concerned with all factors that affect the flow of materials in production and with the ways in which different material flow systems can be created and controlled. In a more narrow sense, it is only concerned with the existing production system. The wider definition includes not only system elements such as labour, machines, and capital, but also functions as organisation, production and process planning, design, plant layout, purchasing, sales and forecasting. The production system decomposition affects the complexity of the production control function, and hence the costs of the required co-ordination and the efficiency of the production system.

For the integral design of both systems, Burbidge (1971) proposes using four principles:

1. simplify the material flow system
2. centralize the responsibility for components
3. reduce set-up time
4. reduce throughput time

The first principle results in fewer material handling efforts, improved throughput rates, and simplified control of production progress and transportation activities. The simplification of material flow should not be restricted to the production departments, but also be applied to the flow of material from suppliers and subcontractors, the flow to distributors and clients, and (on a lower scale) to the flow between work centres and at machines (Burbidge [1962: 35]).

The second principle concerns the organization of inventory control, management of stock locations, and their relationship with production control. The responsibility of inventory control includes the safety stock policy. The responsibility of production control includes the safety time policy. If the responsibility for inventory control of components is not centralized, the level of protection for shortages of components will increase as both the supplying department and the consuming department will protect themselves against shortages.

The third principle recognizes the fact that although set-ups are generally required to offer flexibility to the market, the set-up time is non-productive time for the system. Reduction increases flexibility and allows smaller batch sizes, which reduces work in progress and capital investment. However, reduction of set-up time can only be fully achieved if production control and production system are integrally designed.

The last principle relates to the effects of both systems on the throughput time. A good fit between production system and planning system is required to obtain short throughput times. The design objective ‘reduction of throughput times’ cannot be achieved fully if only one of these systems is the subject of redesign. The portion of slack (waiting time) in the throughput time of products is directly related to the amount of work in process in the production system. Reducing this throughput time therefore reduces the investment in inventory, the number of products that have to be planned and controlled simultaneously, the size and number of stock positions, and so on.

We conclude that in PBC literature, the design of the planning system is not viewed as a process that can be isolated from the design of the production system. The decomposition of the organization into units and the design of the material flow system can help to simplify the planning system. A good fit between this decomposition and the structure (stages) in the planning system will result in a higher performance and ability to further improve the system.

The design parameters of the planning system will determine the resulting throughput time, but the congruity with the design of the production system determines if these throughput times can be realized. For a basic unicycle period batch control system, the throughput time is determined by both the length of the period between successive order releases (the cycle time P, which equals the offset time) and the definition of the stages in the planning system. Stage definition determines the number of stages as well as the contents of the stages (the operations that have to be performed in each stage). The design of the production system will affect these parameter choices, and conversely, the setting of these parameters will impose changes in the design of the production system.

The next sections will focus on the three design parameters of the basic unicycle PBC system. We will discuss the relationship between each parameter of this planning system and the design of the production system.

§ 4.2 Length of planning period P

An important characteristic of the basic unicycle PBC system is the cyclic nature of the production activities within a stage. At the start of each period, a new amount of work arrives in the cells within the stage, and after a period of length P has elapsed, all work has to be finished. Next period production requirements may be slightly different, depending on differences in the sales program for that period. Notwithstanding these variations, at the end of each period, all assigned work packages within each stage have to be finished in order to remain a synchronized system. The choice of the period length P is therefore an important part in designing a PBC system.

§ 4.2.1 Choice of period length

Burbidge [1979: 208] says on the choice of period length: ‘*The choice of programme period is mainly a function of the complexity of the product. ... The problem when choosing the programming and ordering period, is to balance the gains with a short period, such as a reduced investment in work in progress and an increase in the flexibility to follow market changes, against the losses which may be caused by an increase in the number of set-ups*.’

He also presents some guidelines for choosing the period length P:

- there must be enough capacity to complete all the parts/products ordered each period
- it must be possible to complete each batch of parts/products in one period
- effective capacity (which is reduced by set-up activities) has to be acceptably high

These guidelines assume that the production activities that have to be performed during the period are already known when the length of the period has still to be determined. The structure of the production system has therefore been determined, cells have been designed, part families have been defined and allocated to these cells, stages have been defined, and information is available on the approximate size of the batches.

Burbidge first determines the number and contents of the stages and then the period length P. This sequence is not uniformly applied. In a publication on the implementation of PBC, Zelenovic and Tesic (1988) chose first the ‘operating period’ P and for this decision they used information from the bill of materials, production program and the production system itself. The cells were formed afterwards. Note that in their approach, the sequence of the processes that are to be performed in the production system is known when the decision about the period length is taken, but not the division into stages and cells.

The structure of the production system influences the choice of a suitable period length in a PBC system. Burbidge [1975a: 79-80] reports on a production system that had been decomposed into functional departments with a complex interdepartmental material flow. This system had to use a period length of four weeks. An important part of this period length consisted of slack time that was required for co-ordinating these flows. This resulted in a higher period length than the one week period length that was shown to be possible if a cellular decomposition of the production system had been implemented.

A cellular decomposition of the production system makes it sometimes easier to apply overlapping production. This effects a reduction or elimination of micro-waiting times in the process flow of a production batch. To apply overlapping production, necessary conditions are a small distance between the successive machines in the process flow, easily transportation of parts in progress, and machine operators that feel responsible for and are prepared to co-operate in finishing the whole batch as soon as possible. Overlapping production requires a process view, as it tries to reduce the co-ordination losses of subsequent processing steps. In general, such a process view is essential for the success of cellular manufacturing. A cellular production system will therefore be better prepared for applying overlapping production within the cells.

Overlapping production has an important effect on the choice of a period length. The total processing time of the production batch remains constant if overlapping production is applied, so it has no effect on the work load of the system. The make span of the batch, i.e., the time required to finish producing all items of the batch, is substantially reduced, as overlapping production makes it possible to perform multiple production activities in parallel at the same production batch. In § 3.3.6 we already described several aspects of overlapping production. The question remains as to what extent we should use overlapping production and what effect it will have on the period length. In Chapter Five we will answer these questions by doing a mathematical modelling analysis and examine the consequences of applying overlapping production in order to determine a suitable value for the period length.

The choice of the period length has important effects on operational issues relating to the production system. We describe two effects, the *set-up time effect* and the *start/finish effect.*

Set-up time effect

The set-up time effect is mentioned in most literature on PBC (e.g., Burbidge, 1988, New, 1977, Steele, 1998) and we have illustrated it in Figure 4.3. The period length determines the number of production cycles for each product per year. If the demand of product *h* per time unit (D_h) is equally distributed over the periods, then $q_h = D_h \cdot P$, P expressed in the same time unit. If P decreases, the batch size $q_h = D_h \cdot P$ also decreases, but the process still has to be set up for all products *h*, so the total required set-up time per period remains constant. Net capacity therefore decreases, resulting in less slack for this process. We will call this the set-up time effect.

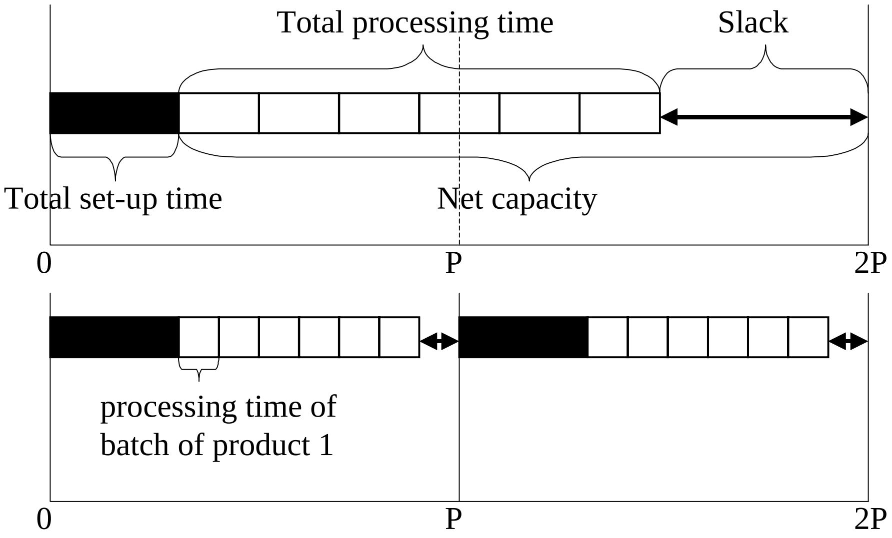

Figure 4.3 Set-up time effect

Start/finish effect

A related effect is known as the start/finish effect. The cyclic nature of PBC significantly affects the net capacity of intermediate processes in the same stage. Intermediate processes (for example, machine II in Figure 4.4) are either preceded or followed by another process in the same stage. Preceding operations cause a start delay, while subsequent operations cause a finish delay. The net capacity of intermediate processes will decrease if the period length decreases, as long as the precedence relationships between operations remain the same within the period. The time required for the start-up or finish activities depends on P, as a smaller P results in smaller batch sizes for these operations. The reduction in P often exaggerates the reduction in these start and finish times, as they contain time necessary for the transfer of a batch between machines. This transfer time does not depend on the size of the batch. We will call this the start/finish effect and have illustrated it in Figure 4.4.

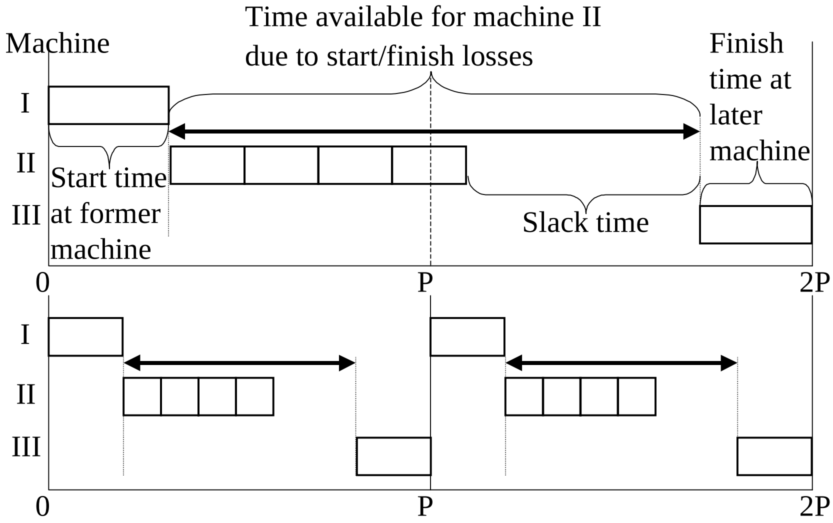

Figure 4.4 Start/finish effect

Literature on PBC implementation proposes various period lengths. Burbidge (1962) recommends either a month or a four-week period. New (1977) suggests that cycles of either two or four weeks are the achievable standard in most situations, while in extreme cases, a six-week cycle may be necessary. Burbidge (1975b) reports on a survey of 40 companies, where the period length ranged from 4 working days to 13 working weeks. Most firms used one month or the equivalent number of working weeks or working days as a period length. Zelenovic and Thesic (1988) and Slomp (1993) propose a period length of one or two weeks. The more recent publications of Burbidge (e.g., 1988, 1993, and 1996) generally recommend using at most one-week periods. Process industries (especially the food industry where shelf life is critical) could use periods of one day or one shift.

Literature that evaluates the performance of PBC also experiments with different period lengths. Yang and Jacobs (1992) tested two, three, and four week period lengths. Steele, Berry and Chapman (1995) tested periods of 1 day, 5 days, and 6 weeks. Steele and Malhotra (1997) used 3, 4, 5, 6, and 7 days. Kaku and Krajewski (1995) used a minimum cost search algorithm to determine a suitable period length in their experiments. The integer valued period length that they obtained was 2, 3, 4 or 5 days.

The various period lengths that we have encountered all have one comparable feature: they are expressed in some common time measure, either months, weeks, days, or shifts. Are there any reasons to restrict the length of a period to these time measures? Or is it also appropriate to choose 7 ½ shifts of 8 working hours as a period length?

The practical aspects of a suitable period length are an important factor in the design of the planning system. The planning system has to offer synchronziation of material transfer between stages, and the way this is guaranteed is by providing transparent work progress within the system. This transparency is only present if all people in the system are aware of the period length and the actual finish time of a period. The transparency is also used in relations and communication with suppliers and customers. In general, communication with customer and internal sales department can be expected to be easier if a natural time measure is used. Information on the date of usage has to be sent to the supplier. An easy to use period length is often preferred, both by the supplier and the internal material receiving function, as it is easier to remember that new material should arrive (knowledge of deadlines) when a general rule is applied. The same holds true for arranging program meetings with the planning board (same day, same time). The essential prerequisite is that the period length creates a natural rhythm for the production system.

Finally, we want to make the observation that the repeating pattern of production activities that results through the use of a fixed cycle has a positive effect on the learning behaviour of the operators, as long as these workers indeed repeat these activities themselves. The number of working shifts in a period can disturb this learning effect. If the next cycle starts with a totally different work force, this may result in abeyance of these learning effects. An increase or decrease of the period length that facilitates the occurrence of a repeating pattern may result in an enhanced system design as the production system improves.

§ 4.2.2 Trade-offs in the choice of period

Changes in the period length have consequences for several aspects of the design of a production structure and system performance. Figure 4.5 shows us the effect of a reduction of the period length P to P`. We see that both the manufacturing throughput time and the order lead time or forecast horizon (if one produces on forecast) decrease if P decreases. Literature on PBC gives the following additional insights:

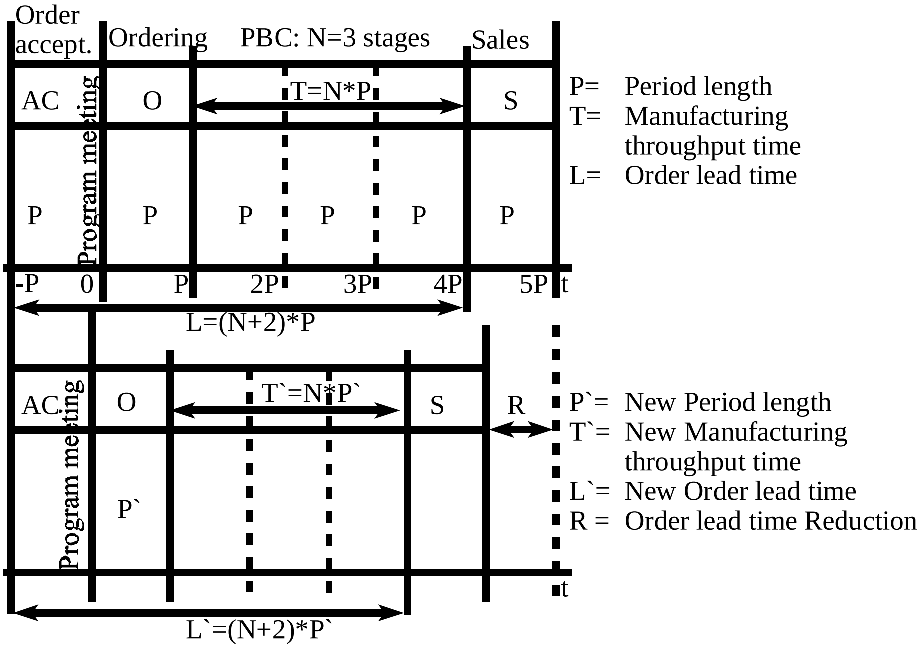

Figure 4.5 Effect of reduction of period length P

New (1977) notes that the shorter the period length, the more flexible the production system will be. Furthermore, the demand forecasts for the sales period become less uncertain, as this sales period is reached earlier in time. It should be noted that the flexibility to which New points is related to the response time to the market if some products are made to stock.

Whybark (1984) emphasizes the positive effects of a shorter period length, and mentions a quicker customer response, a higher potential market share, a higher percentage of orders that can be made strictly to order, and a lower cycle stock. On the other hand, a higher period length will result in higher manufacturing efficiency, fewer set-ups, lower manufacturing costs, and larger purchase quantities. Note that these benefits are strongly related to the design of the production system. Furthermore, a higher period length leads to a higher risk of unbalanced end product stock resulting in an increase of unsaleable stocks and an increase in stockouts for products for which the demand is greater than expected. The latter may result in an increase in the overall safety stock level.

Suresh (1979) notes that reducing the cycle time in PBC is consistent with the objective in MRP systems of reducing the time bucket size and results in greater precision in timing the orders and greater flexibility since firm orders need to be given only for the immediate period.

Yang and Jacobs (1992) found that a higher P results in a decreasing mean order tardiness, and less variety in order tardiness. Process dependability therefore increases as P increases. However, this is accompanied by an increase in the work in progress and the various stocks in the system. For this reason, they conclude that increasing the period length does not seem like a good alternative to improving delivery performance.

With respect to the flexibility, we note that both the volume flexibility and the mix flexibility may decrease if the period length is shortened. Volume flexibility may decrease because the ordering period is smaller, which leaves less time for making adaptations to the capacity in the production system. Mix flexibility decreases because of the set-up and start/finish effects, which leave less slack time. However, if we face lumpy demand, the number of set-ups per period may decrease if the period length is shorter, which allows more remaining capacity for production and hence an upward shift in volume flexibility.

A reduction of P also affects the forecasting effort. Two factors have to be taken into account. Firstly, a reduction of P results in a smaller sales period for which the demand has to be forecast. Theory on forecasting teaches that a forecast for a smaller period is in general less reliable. A less reliable forecast combined with decreased mix flexibility results in an exaggerated sensitivity of the system to changes in demand. This will have important consequences for the design of the production system.

Secondly, if P is reduced, the frequency of forecasting increases, since for each program meeting, a forecast for the next sales period has to be produced. This leads to an increase in the work load of the forecasting function within the organization. This increase in work load is independent of the required increase in forecasting quality due to the first factor that we mentioned. Note that PBC systems that produce on order will not encounter the two forecasting problems mentioned, but the increased sensitivity to changes in demand and the increased effort required of various departments that are involved in co-ordinating the transformation process will also become apparent in these organisations.

Our discussion on the relationship between the production system and period length has demonstrated the importance of determining the period length in the structuring of a basic unicycle period batch control system. Although we have presented several insights into factors that are important when determining a suitable period length, we have not paid any attention to approaches that help to determine a suitable value for the period length. It should be noted that other planning systems, such as MRP and Kanban, also lack such approaches. In Chapter Five we will develop several mathematical models that may be used in order to determine a value for the period length. The effect of period length determination on costs and system performance will also be addressed.

The effect of stage definition on the design of the production system and the possibility of achieving the overall system objectives have to be clarified first. Stage definition consists of determining the number of stages N, which is treated in the next section, and determining the contents of the stages, which is discussed in Section § 4.4.

§ 4.3 Stage definition: number of stages N

The relationship between the number of stages and the structure of the production system is important to examine. Production systems are generally decomposed into several units. The characteristics of these units may vary. A global distinction between various production system characteristics in line production, batch production and jobbing production has been made by Hill (1991). The varying characteristics and the required logistical performance place different demands on the planning system that is used for the planning *within* these units. If the production units each have a different internal structure and local planning system, co-ordination between these production units still has to be performed. This co-ordination concerns not only sequential co-ordination (goods flow, resource flow, information flow) between units, but also simultaneous and latent relationships, as discussed in Chapter Two.

Sequential co-ordination of the goods flow *between* successive units can be performed in several ways. In general, a distinction should be made between push or pull co-ordination mechanisms. Both mechanisms assume that each unit acquires an amount of time from the overall logistical planning system to perform the tasks. This amount of time can be seen as being the maximum lead time that is available to the unit for performing the task. If the planning system uses such a lead time offsetting procedure for the co-ordination of the goods flow between the units, then the resulting planning system structure will be strongly related to the decomposition of the production system into units. Hence, in these cases the definition of these units will affect the design of the planning system.

PBC uses such a lead time offsetting procedure between *stages*, as we described in Chapter Three. An important facet of the basic unicycle PBC system is that each stage is provided with the same internal lead time. This leads to a synchronization of the material movements between the stages. However, the question remains as to how the departmental structure of the production system, i.e., the units, should be used for the definition of the stages.

This problem of defining the structure of the planning system is not unique for PBC. Other planning systems, such as MRP and Kanban, also have to apply a decomposition of the planning structure. These systems often apply a decomposition that resembles the existing departmental, cell, or work centre structure, without taking notice of the possibility of finding an improved decomposition of the production system that takes account of the interaction between both systems.

PBC literature suggests redesigning the production system using Production Flow Analysis. The resulting decomposition of the production system should be used to determine the structure of the planning system, and more specifically, the number of stages in the planning system. We will examine the contribution made by this procedure in more detail in the next subsection.

§ 4.3.1 Processing stage definition with Production Flow Analysis

Production Flow Analysis (PFA) has been extensively described in Burbidge (1971, 1979, 1989a). The main elements of this procedure are:

factory flow analysis	Divide the production system into departments that can completely process *a set of parts*. A division *according to major differences in processing type* will give the simplest possible interdepartmental material flow system
group analysis	Allocate the machines and operators within each department to groups, the parts to families, and finally match the families with the groups into cells. Cells should have an expected work load evenly distributed over the year and high enough to justify combining these machines, operators, and parts into a separate organizational unit
line and tooling analysis	Design layout and material and resource flow system between machines in the cells

A production system that is designed using PFA will probably consist of various cells with a group layout, but this need not always be the case. The assembly department might consist of several production lines, while the component processing department might still be functionally organized as one group that produces all part families.

This description of PFA consists of two elements that we have to study in more detail in order to understand the principles behind the proposed decomposition of the production and planning system:
- the definition of a '*set of parts'*
- the assumption that a division *according to major differences in processing type* will give the simplest possible interdepartmental flow system and should therefore be applied when decomposing the production system.

Decomposing the production system according to a 'set of parts'

How the decomposition of the production system is carried out will depend on the definition of a 'set of parts'. The definition of the set of parts therefore controls the decomposition of the production system. However, it is not obvious how the set of parts should be defined. We give three examples:

If the final products are divided into several families and each family is considered a '*set of parts'*, we will obtain a vertical decomposition of the production system, i.e., each department will completely process a family of final products. Complete processing means that all operations that are required for the products are performed in one department, for example, from raw material processing to assembly.

Alternatively, if we define all hydraulic components as one '*set of parts'* and all electronic components as another '*set of parts'*, we will obtain a totally different decomposition of the production system. That type of decomposition is oriented towards the production of modules.

We can also define the '*set of parts'* in terms of the output of a processing stage. A production system generally consists of various processing stages, defined according to the main processes that each provides and the sequence in which they are required. The differences between these main processes may impose specific requirements on the working environment, material handling equipment, climate, and so on. For example, in metal ware production we can make a distinction between raw material processing, components processing, sheet metal production, welding, surfacing, painting, subassembly, assembly, and so on. If we define the '*set of parts'* according to the processing stages that are present in the production system, we will obtain a horizontal (functional) decomposition of the production system into departments identical to the processing stages. It should be noted that a functional decomposition of the system into processing stage departments does not mean that the cells resulting from group analysis will be functionally organized as well.

The use of processing stages in production system decomposition

The second element we want to examine is the assumption that the simplest possible *inter*departmental material flow system will come about if processing stages are used to define the departments. It is well known from literature that the complexity of material flow systems is influenced by the layout of the production system. A line layout has standardized the flow of material on the line and attention can be focussed on the flow of material to the line and the flow of products from the line. For functional layouts, we have to distinguish between systems with different and bi-directional flow patterns between the functional units, which will result in a complex material flow system, and systems with uni-directional flows between the functional departments. The latter situation results in a less complex material flow system. It can be interpreted as a flow shop, where the time required in each station (functional department) varies per job, but the flow between the stations is equal for all jobs.

If the boundaries of processing stages are used to define the departments, we will obtain a flow shop like functional decomposition of the production system, as defining processing stages involves sequencing the main processes in the product routings. The flow that departments face is uni-directional (no back flow) and the number of different flows from a department to other departments is restricted to the number of downstream departments.

We now return to the issue of the validity of the assumption that the simplest possible *inter*departmental material flow system will come about if processing stages are used to define the departments. We conclude that a decomposition of the production system into departments according to processing stages may indeed result in an improved flow between the departments if compared with a traditional functional organized production system. The latter apply a much higher degree of functionalisation, resulting in far more departments with more complex routings between them. However, a processing stage definition is only a first step towards a simplification of the interdepartmental material flow, and will surely not result in the simplest possible system.

The simplest possible *inter*departmental material flow system will come about if we have a production system where each department completely makes a family of products. In such a case, there will not be any material flow between the departments at all, which makes the required planning system quite easy to design. However, such a decomposition will probably result in other inefficiencies in the production system: for example, increased training costs for operators, low utilization of machines, and so on. Hence, a trade-off between efficiency of both the production system and the planning system has to be made.

Alternative stage definitions in Production Flow Analysis

The decomposition of the production system into processing stages is not a simple matter, but requires an explicit decision. Burbidge [1993: 548] mentions that '*a problem with GT has been in the choice of processing "stages". In general, we have tended to accept the existing stages found in traditional factories, which are normally bounded by stores'.* In [1962: 293] he had already stated that '*for simplicity, this division is normally made on some arbitrary basis*'. These quotations make it clear that it is not necessary to define the stages according to the major type of process that is applied. In fact, in his 1993 publication, Burbidge discusses several situations where he explicitly deviates from this type of division. These deviations are initiated by the design of the planning system structure. However, they do not originate from the PFA method itself, although factory flow analysis strives to combine several subsequent stages into departments in order to further simplify the material flow system.

New (1977) sees the division of the material flow system as a separation of the factory into ‘incompatible’ departments. The next step of PFA, group analysis, results in combining facilities and parts of these departments into cells. When this group analysis has been completed for all departments, he expects it may further be possible to combine cells with common component flows that occur in different departments. This would create a situation with sections of one cell in physically different locations, where the cell is treated as a single unit for planning purposes (New [1977: 228]), while normally a cell only exists within one processing stage (ibid. [1977: 221]). Burbidge (1971) notes that incompatibility is partly a function of the choice of machinery, and can often be overcome by investments in equipment, facilities, foundations, control, or other things that enable a combining of these processes. Hence, PFA may also suggest separating a process according to an economic perspective.

The treatment of intermediate subcontracted operations, and of auxiliary and service processes causes another problem in production system decomposition. Subcontracting can be treated as a separate stage, but this may cause a back flow. These operations could also be eliminated through replanning the process routes. The specific co-ordination requirements that originate from such a production system design were discussed in Chapter Two.

We will examine the consequences of the appropriate decomposition of the production system for the decision about how to decompose the PBC system into stages. These decisions can be distinguished.

§ 4.3.2 Decomposition of the Period Batch Control system into stages

Steele (1998) notes that PBC matches the stage-like structure of the cellular production system and creates a phased flow of production lots through these stages. In fact, PBC is designed for the management of stages of production corresponding to periods of time. He concludes that stage definition is nevertheless not well understood.

Publications on PBC do not pay much attention to the exact definition of stages in PBC, as noted in § 3.3.3. The main distinction is between an assembly stage and ordering, e.g. the procurement of the required components. A division of the ordering stage is not given in advance. There must simply be enough time in the ordering schedule to perform all required processes between ordering and completion of the parts. For some production situations, this may include material acquisition, or product design, while others will have raw material in stock or do not need to redesign the products.

If items pass through a number of different departments, Burbidge (1962) divides the ordering stage into subdivisions. Each subdivision receives a target date on which all work on the batch should be completed. This division is made on an arbitrary basis, as we have noted before.[2] If we analyse the stage definition approach of Burbidge in later publications (e.g., 1975a, 1989a, 1989b, 1993), we conclude that there are inconsistencies in his descriptions of the stages in the ordering schedule, mainly with respect to the timing of activities (the parallelogram) and the way he treats (or ignores) parallel processes.

We conclude that the way Burbidge determines stages does not provide us sufficient help in making this important decision in PBC system design. We have to further explicate factors that should be considered in this decision process. We assume that the allocation of operations to cells has been performed, i.e. it is known *where* the operations are being performed. Stage definition determines *when* these operations are being performed.

A framework for determining the stage decomposition in PBC

We propose a framework for determining the decomposition of the PBC system into stages. The framework identifies the various choices that have to be made in order to provide the planning system with an adequate structure. It should be noted that the structure of the planning system is equivalent to the number of stages in the PBC system.

Before identifying the stages, the system objectives should be formulated and prioritized in a way such that they can be used as guidance in designing the planning system[3]. To make an integral design for the production and planning system, we need to know *what, when* and *where* to deliver (see Figure 4.2). After these decisions, we should determine specific system objectives in terms of:

- speed (lead time)
- dependability (tardiness)
- flexibility
- quality
- costs

According to the weighting of these system goals, a trade-off should be made with respect to the impact that these goals may have on stage definition. From a lead time perspective, it may be wise to combine several operations into a stage, but not from a dependability perspective.

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[2] The ideas for the subdivision stem mainly from the operation of the related standard batch control system (Burbidge, 1960). In this system, he introduces the decomposition of the production system into *sections*. Sections receive order lists with all item orders having common due dates. A section order may be broken up into several *stage sheets* if different groups of parts that are needed for the same batch of products are required at different due dates. The division of the production system into sections and stages in the standard batch control system is strongly related to the actual product structures as well as the existing organisational division.

[3] We would like to see these objectives used also in defining the structure of the production system, but a decision to do this is often driven by the differences in processes, as we have shown in the former subsection.

As the weighting and priority given to the five system objectives will vary for each production situation, we cannot conjecture in general about stage definition. However, if we have system objectives in a specific situation that are ranked according to priority, we are able to identify relevant aspects of the production system or planning system that will influence these objectives and to identify the impact of stage definition on these objectives.

The desired number of stages in a PBC system depends on characteristics of both the production system and the mix of system objectives that the planning system aims at to achieve. Note that each stage in the basic unicycle PBC system obtains the same amount of time (one period of length P) in order to complete the processing steps of this stage. Therefore, the length of the period may influence these characteristics as well as the possibility of achieving the objectives. For example, if a small throughput time (speed) is more important than quality or flexibility, processing steps may be combined into one stage. Alternatively, the shorter throughput time may be obtained through a smaller period length and separate stages, as we discuss further in Chapter Six.

In our framework for planning stage definition, two factors stand out:

- there might be a significant change in *uncertainty* between two processing steps, which may indicate a useful position of a stage boundary (production system related).
- there might be a significant change in *required accurateness of control* between two processing steps, which may indicate a useful position of a stage boundary (planning system related).

Table 4.1 shows how these factors can be applied to the various objectives mentioned before. The examples give an impression of the influence of stage decoupling on system objectives.

With respect to the change in uncertainty, we need to consider that this uncertainty may be inherent to either the conversion process itself or the co-ordination needed between the two successive processing steps. For these types of uncertainty, Susman (1976) introduced respectively the terms *conversion uncertainty* and *boundary transaction uncertainty.* In Chapter Eight, we will discuss these types of uncertainty further.

The accurateness of control that is required for successive processing steps may vary. The weight that is given to a specific system objective influences the attention that should be paid to this control problem. We can already identify a change in the required accurateness of control between two successive processing steps without specific knowledge of the weight of the related system objective. However, the magnitude of this change cannot be determined without knowledge about the importance of achieving this objective. If the achievement of a system objective prescribes different control approaches for successive processing steps, we expect this will be more difficult to accomplish within the same stage then between stages. This explains why we have indicated this a separate factor.

	Production system: change in *uncertainty*	Planning system: change in *accurateness of control*
Speed	If the speed of a preceding processing step varies, for example, yield uncertainty in wafer processes, stage decoupling functions as a buffer that may lead to an increase of the output (cycle time) of the whole process.	If a processing step is to be performed at a bottleneck, stage decoupling may help to improve the utilization of the bottleneck, because of an improved control of the sequence of release of work to the bottleneck, and of the availability of material, resources, and information.
Dependability	If the addition of a processing step to a stage results in a substantial increase in uncertainty of whether the work will be finished within a period length P, stage decoupling can be considered.	If a processing step requires the availability of several incoming flows, e.g., an assembly operation, stage decoupling can be considered.
Flexibility	If the addition of a processing step to a stage results in a substantial increase in uncertainty about whether the intermediate items can be used effectively, decoupling of the stage can be considered. See, for example, the customer order decoupling point.	If the next operation requires a different control approach, because the required flexibility has to be found externally instead of within the system, stage decoupling can be considered in order to obtain time to prepare this decision.
Quality	If there is uncertainty with respect to the exact specifications of a processing step (e.g., art work, design processes), stage decoupling allows an improved control of the final quality.	If a processing step requires a different quality control approach, e.g., presence of an external quality inspector, stage decoupling can be considered in order to buffer the remaining operations from this dependency.
Cost	If the cost of a processing step depends on the availability of a specific grade or dimension of the input material, stage decoupling will allow the operators more choice when they select the required material, leading to lower cost.	If a processing step requires expensive components from an outside supplier, stage decoupling before this step can help to improve the control over working capital increases and lower the total cost.

Table 4.1 Examples of factors that influence PBC stage definition

Production system decomposition and co-ordination requirements

The type of work that is controlled by PBC will generate different co-ordination requirements, as discussed in Chapter Two. This influences the structure of the planning system. In general, assembly operations should be distinguished from component processing operations, as they generate sequential relationships with more preceding operations. Furthermore, the required accurateness of control is higher, as all parts have to be available at the start of the assembly. Therefore, a natural division between the stages will result, as this guarantees that all parts have been completed or arrived before assembly starts.

Conversely, separation of component processing and finishing in subsequent stages is not obvious from a planning point of view. Although the processes are incompatible, making transportation of the material necessary, this need not result in a separation of the two processes into different planning stages. For example, the finishing operation can be organized as a service centre, or can organizationally be allocated to a component processing cell without physically combining both processes at one location. In both situations, the structure of the planning system does not change, although the processes are incompatible. Reasons other than these co-ordination requirements may still lead to the separation of both processes in subsequent stages.

From this, we conclude that the definition of stages in a PBC planning system does have to take on some of the characteristics and decomposition of the production system, but that there are also factors from the planning system that have to be taken into account.

The number of ‘unavoidable processing stages’ in the production system cannot be used directly for a useful definition of stages in a PBC system, as is done by Burbidge. The main reason for this is that the number of processing stages does not give enough insight into the complexity of the co-ordination problem between and within the stages, no matter whether this complexity is caused by conversion uncertainty, boundary transaction uncertainty, or the required accurateness of control. Planning systems should handle this co-ordination complexity in an adequate way and need therefore to be structured such that this co-ordination can be performed. Our framework provides a systematic way of setting the number of stages.

§ 4.4 Stage definition: 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. Our framework indicates that the allocation of operations to stages influences the start/finish losses, dependability, bottleneck utilization, subcontracting co-ordination problems, and investment in working capital. Other effects, such as the set-up-time effect, are not affected by the allocation of operations. They only depend on the number of stages N or on the period length P.

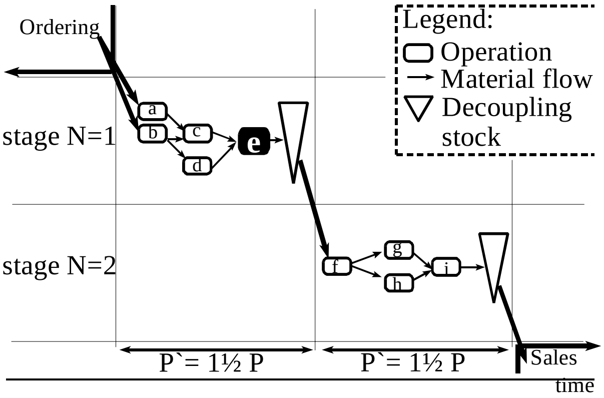

Figure 4.6 Original stage allocation

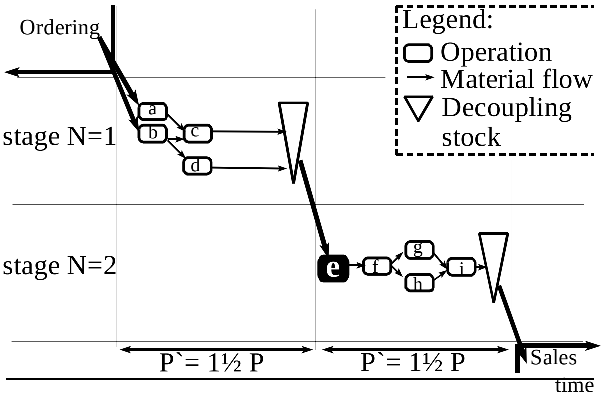

Figure 4.7 Alternative stage allocation

We illustrate the importance of stage contents determination in Figure 4.7, which shows an alternative allocation of operations to stages compared with Figure 4.6. The reallocation of operations affects the workload distribution of resources over the period. The two operations *e* and *f* were allocated to different stages, but are now allocated to the same stage. Hence, in Figure 4.7, 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 starting time of *following* operations in stage 2 and for the latest finishing times of the *preceding* operations in stage 1. It therefore affects the workload distribution of the resources that perform these operations.

§ 4.4.1 The relationship between cells and stages

We have criticized the use of a technologically based division of the production system into processing stages as a design criterion for the structure of the PBC system. However, such a division makes the allocation of operations to the stages quite easy. The framework that we have proposed should help to determine suitable stage decoupling points in a PBC system. A change in the uncertainty between two successive processing steps may be a valid reason for introducing a stage decoupling point. This raises the question of the relationship between the cellular decomposition of the production system and the occurrence of a change in uncertainty between successive processing steps when determining the contents of stages for PBC. The framework allows for stage contents that involve the presence of multiple cells delivering to each other within the same stage, as long as there is no substantial change in uncertainty or required accurateness of control.

PBC does not provide sequential co-ordination between cells within a stage. Another part of the planning system has to cope with the remaining co-ordination within and between cells in a stage, see e.g., Burbidge (1988). The length of the period and the number of cells in a stage will influence the complexity of the remaining co-ordination between cells in a stage. We will discuss this remaining co-ordination in Chapter Eight, but firstly we will amplify upon the relationship between cells and stages in more detail.

We want to determine how desirable it is to define stage contents as being not identical to the contents (operations) of one cell. If the contents of both are identical, we have stage boundaries that exactly overlap with cell boundaries. All operations for a future period of demand that are performed within the same time bucket (the stage) are performed within the same organizational unit (the cell). The benefits of such an allocation are mainly that there will be simplified and transparent co-ordination between the cells. Will these benefits still be present if we apply a different allocation of operations to the stages? We will discuss this problem in the next two subsections according to the following questions:

- Should we design stages with operations performed in various cells?
- Should we design cells with operations performed in various stages?

§ 4.4.2 Stages with operations performed in various cells

Situations with various cells within a stage are depicted in Figure 4.8. Cells X1, X2, X3, X4, and Y are all active within the same stage. Cell X1 is sequentially related to cells X2 and X3. The latter two are sequentially related to cell X4. Cells X2 and X3 are simultaneously related within the same stage. All cells X1, X2, X3, and X4 are simultaneously related to cell Y.

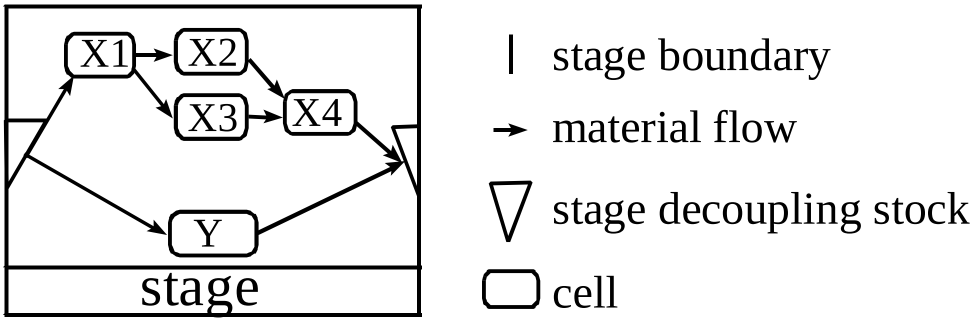

Figure 4.8 Operations involving various cells within the same stage

Simultaneously related cells within a stage

Cells that are only simultaneously related within the same stage can produce independently. Their relationship does not constrain the production activities, but it may provide useful information on priorities, as they both produce for the same sales period demand.
There is no objection to allocating simultaneously related cells to the same stage. Allocating them to different stages might increase the number of stages and hence the throughput time, without any benefit with respect to the required co-ordination effort.

Sequentially related cells within a stage

Sequentially related cells within a stage cause start/finish effects, which may reduce the performance of the system. The operations of the sequentially related cells can be combined within a new cell, which would make it easier to co-ordinate the relationships between the successive operations and might diminish the negative impact of the start/finish effect.

However, there are reasons for not preferring such a redesign. These reasons are derived from the three categories that were described in detail in Section § 4.3.1: economic reasons, group effectiveness[4], and environmental issues.

Economic	utilization, material efficiency, specialization
Group effectiveness	group size and synergy, productive multi-functionality, variety of education level
Environmental	locative constraints of processes (e.g., foundation, noise, dust), incompatibility of processes

Table 4.2 Reasons for allowing various cells within the same stage

Economic and environmental reasons will be prevalent if some of the operations in a cell cannot be allocated towards other cells that also require these processing steps. The sequential relationships between cells can be divided into linear, convergent and divergent relationships.

With a convergent or divergent relationship, various cells within the stage all have a sequential relationship with one particular cell in the stage. This isolated cell could have been duplicated to create two or more simultaneously related cells. However, this solution has a cost in terms of the economic or environmental reasons mentioned. Avoiding duplication of resources, material inefficiencies, cost of investing in the required environmental conditions, and reduction of specialization level may be more important than organizational or logistical reasons that would prefer a combination of these operations in one cell.

For a linear structure, the economic reason is not valid. The other reasons for separating the flow within a stage, such as environmental issues and social effectiveness of the work group may still hold. Work groups might benefit from separation into two groups of workers because of an unproductive group size or a huge difference in culture or educational level. The factors that we discussed do not provide a reason for a stage decoupling in the planning system (no change in either uncertainty or required accurateness of control). It is the quality of the decomposition of the production system into cells that might improve. Therefore, such a decomposition of the production system does not make it necessary to separate its processing steps into different planning stages.

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[4] Defined by Hackman (1982) in his normative model of group effectiveness.

§ 4.4.3 Cells with operations performed within various stages

A distinction should be made between cells with boundaries that exceed the stage boundaries (cell X in Figure 4.9), and cells that are simultaneously active in various stages because the processing steps can be performed in parallel (cells Y and Z in Figure 4.9). In basic unicycle PBC systems, the situation of cell X cannot occur, as the cycle time for cell X is smaller than the offset time. However, the situation of cell X can be viewed as a special case of cell Z that is simultaneously active in various stages. If we allocate several of the operations of cell X to the first stage and other operations to the next stage, we will still be operating a basic unicycle PBC system.

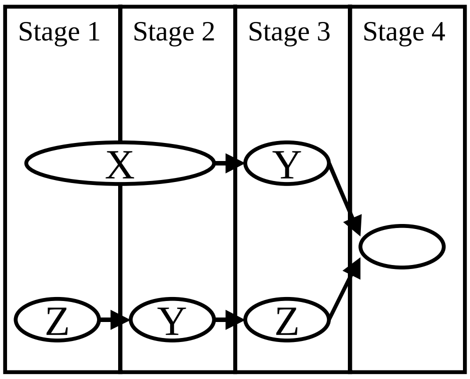


Figure 4.9 Cells with operations performed within various stages

Cells that are simultaneously active in various stages

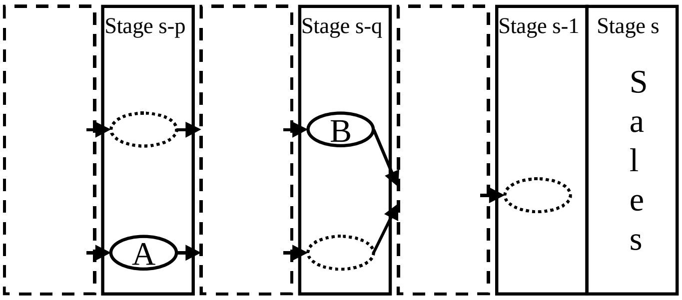
Cells X, Y and Z are simultaneously active in various stages. Cell Y performs the *same type of operations involving different components* that both have to be worked into the same product. Cells X and Z perform *different types of operations* in subsequent production phases involving the *same components* of the same product. Cell Z faces a back flow between stages.

Suppose we assume that cells have to perform operations for a specific product within one single stage, as described in literature on PBC (e.g., Burbidge [1993: 544], [1996: 215]). We would then have to avoid cell X, Y, Z situations, and to redesign product routings in order to avoid back flows. This would lead to a reallocation of the operations carried out in a cell to an earlier stage. The operations carried out in cell Y in stage 3 would be reallocated to stage 2. However, performing all operations within the earliest stage in which a cell is active would lead to temporally unused stock during the next period. The reduction in work in progress is a strong argument for allowing cells of type Y to become simultaneously active in various stages.

Cells of type X may face the situation that the sequence of operations that have to be performed within the cell takes more time than available within one stage. If all the operations of this cell were allocated to the same stage, this would require high co-ordination costs (for overlapping production), overtime costs, or result in a low dependability. The cell X situation cannot be used if a single operation takes more time than available within a stage. Dividing such an operation over two stages will result in the periodic release of an amount of work load that exceeds the time available within a period. The required capacity for each operation that arises in both stages in the process routing of cell X has to be smaller than half the period length.

Another argument for preferring cells to be simultaneously active in various stages is related to the *effect of cell work load fluctuation over the periods*. It may be valid for all three types of cells (X, Y, and Z) as long as they partly use the same type of capacity (machine or labour) in both stages. This will be shown using some elementary mathematics.

The work load of a cell depends on the number of products it has to make within a period. Suppose the cell produces two different part types A and B that are both worked into a single end product. Each end product requires k_a parts A and k_b parts B (the k's are explosion factors). Every period, the work load of the cell consists of a batch of parts A and a batch of parts B. The size of the batches of parts A and B that are produced within a period in the cell are simply a multiple of the explosion factor and the demand for this end product during the sales period for which they are made.



Ⓐ Cell producing part A for the end product sales in period s

Ⓑ Same cell producing part B for the end product sales in period s

◌ Other cell

Figure 4.10 Work load distribution if cells are simultaneously active in various stages

Figure 4.10 shows an example where parts A are produced p periods ahead and parts B only q periods ($p \geq q$) before they are delivered to a customer. The parts that are produced in the cell during one period t are therefore possibly intended for different sales period demands: part A for sales period $t+p$, part B for sales period $t+q$. The work load of the cell depends on the amounts of the end product demanded during these two periods.

Let D_s be the demand for the end product in sales period s. We will assume that there is no trend, seasonal or otherwise, influencing the demand per period. However, demand may fluctuate according to a stochastic process. We will assume D_s to be independent of s and identically distributed throughout all sales periods with mean and variance (μ_D , σ^2_D). Hence, D_s i.i.d. $\approx (\mu_D , \sigma^2_D)$.

The demand for parts A in period t, $X_{A,t}$ is a linear transformation of the demand for the end item in period $t+p$, $k_a \cdot D_{t+p}$, and hence is independent and identically distributed with mean and variance ($k_a \cdot \mu_D$, $k_a^2 \cdot \sigma^2_D$). Demand for $X_{B,t} = k_b \cdot D_{t+q}$ i.i.d. $\approx (k_b \cdot \mu_D , k_b^2 \cdot \sigma^2_D)$.

In order to determine the distribution of the total work load for this resource in the cell in period t, we have to find the distribution of the sum of these two random variables
$X_t= X_{A,t} + X_{B,t} = k_a \cdot D_{t+p} + k_b \cdot D_{t+q}$

The mean of this distribution is the sum of both means: $k_a \cdot \mu_D + k_b \cdot \mu_D = (k_a + k_b)\cdot \mu_D$

The variance of this distribution consists of the sum of the two variances and the covariance:
$\mathrm{Var}(X_t) = \mathrm{Var}(k_a \cdot D_{t+p} + k_b \cdot D_{t+q}) = k_a^2 \cdot \sigma^2_D + k_b^2 \cdot \sigma^2_D +2\, k_a\, k_b \cdot \mathrm{Cov}(D_{t+p},D_{t+q})$

If $p\neq q$, the independence of D_{t+p} and D_{t+q} causes $\mathrm{Cov}(D_{t+p},D_{t+q}) = 0$, hence:
if $p\neq q$, $\mathrm{Var}(X_t) = \mathrm{Var}(k_a \cdot D_{t+p} + k_b \cdot D_{t+p}) = (k_a^2 + k_b^2) \cdot \sigma^2_D$

However, if $p=q$, we have $\mathrm{Cov}(D_{t+p},D_{t+p}) = \mathrm{Var}(D_{t+p})$ and hence:
if $p=q$: $\mathrm{Var}(X_t) = \mathrm{Var}(k_a \cdot D_{t+p} + k_b \cdot D_{t+p}) = (k_a^2 + k_b^2 +2\, k_a\, k_b)\cdot \sigma^2_D$

From this analysis we conclude that if a cell is simultaneously active within various stages ($p\neq q$) in respect of the same product, the variance of the work load will be $2\, k_a\, k_b\, \sigma^2_D$ smaller than if the cell performs all operations for this product within the same stage. The mean work load is not influenced by this allocation decision. To sum up, if demand between the periods is uncorrelated, cells are more flexible if they are simultaneously active in various stages.[5]

We have seen that there are two reasons for cells to become simultaneously active in various stages: lower work in progress and improved flexibility. However, there are also reasons for not allowing cells to be simultaneously active in several stages. The reasons that we will discuss are:

1 reduced standardization of period production requirements
2 unstable sequencing policy within cells
3 increased number of sequential relationships with other cells

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[5] The same type of argument can be used for cells that obtain their work load not from just one end product, but if the work load originates from several products. The flexibility of these cells and the system as a whole increases due to the independence of end item demand. At the same time, we then incur a higher number of set-ups per period, which may again decrease the flexibility.

re. 1 If a cell produces simultaneously for different sales periods of end product demand, the originating period of particular production requirements will be less obvious, making the system less transparent. If all production activities carried out within a period have a direct relationship to the number of end products demanded some periods later, the number of parts that have to be produced in a period is easy to calculate and discrepancies with the actual production quantities in the period are quickly detected. This makes capacity planning easier.

re. 2 If there is a single end product which creates production requirements for several parts in the cell, the sequencing policy within the cell will be less stable. If all production activities are directly related to one sales period, the optimal sequence for minimizing the make span within the cell will remain constant over the periods, in spite of the fluctuating demand over the periods. If the production activities are related to two distinct sales periods, the optimal sequence for minimizing the make span will change when demand varies. This means that the transparency of the capacity planning of the cell diminishes if cells become simultaneously active in various stages. The efforts of the cell scheduler should not then be restricted to capacity alterations (overtime, hiring) or preparing overlapping production, but should be extended to re-sequencing. It is usually difficult to find an optimal solution for these re-sequencing problems. Where there are various end products, re-sequencing is almost always necessary if optimal make span performance is to be obtained.

re. 3 Another disadvantage of the cell being active in separate stages is that the cell can obtain a lot of sequential relationships with other cells within a stage, either as a consuming or a supplying cell. Co-ordinating these relationships can become rather complex if the number of relationships increases. If the cell produces parts for temporally unused stock during the next stage or stages, a kind of slack is added, making it unnecessary to formally co-ordinate the cells that consume these parts. This allows the cell to concentrate on the co-ordination with the cells that use the output directly during the next period.

These factors may be important, but do not justify the preference in PBC literature to allocating all operations that have to be performed within a cell to the same stage. To summarize, the main disadvantages of such an allocation are:

- increase in work in progress and holding costs, as this allocation does not make a distinction between operations that require further processing in the next stage and operations that will have to wait a complete period before they will proceed
- increase in overtime costs or co-ordination costs (extra transfer batches), 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
- decrease in flexibility, as this allocation is more sensitive to variations in the work load
- increase of start/finish losses for bottleneck processes in a cell, as this allocation does not take into account specific loading problems that arise due to the periodicity of the system

We conclude that in general it is neither necessary nor desirable to allocate all operations that are to be performed in the same cell to the same stage.

§ 4.4.4 Relevant factors for allocation of operations to stages

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.

The framework given in Section § 4.3.2 provides support for the stage allocation decision. The system objectives are speed, dependability, flexibility, quality, and cost. It can be more or less easy to identify changes in either uncertainty or required accurateness of control with respect to these objectives. Changes with respect to quality and flexibility are often more easily identifiable as reasons for allocating successive operations to different stages then changes with respect to the other three objectives. The latter objectives concern the time/cost trade-off. In a basic unicycle PBC system, speed is determined by the product of N and P. Therefore, given N and P, the allocation of operations to stages will not influence the speed objective.

The decision to allocate successive operations to a (possibly different) stage based on the time/cost related objectives is strongly influenced by the length of period that has been decided on. In Appendix B, we will demonstrate this trade-off in a mathematical model that supports the allocation of operations to stages. This model determines an appropriate allocation of operations to stages, given a period length P and a number of stages N. We will discuss the principles that we apply in this modelling approach.

Costs are influenced by the timing of increase in working capital. Operations allocated to an earlier stage than N cause the required input material to be present on the working capital list for a longer time. Another factor influencing the increase in working capital is the type of operation. Operations differ in the amount and costs of the required inputs and processing time. Hence, by allocating operations to stages, we control when the working capital will increase. The lowest cost solution would be to allocate all operations to the final stage N.

Dependability is related to the time aspect of the performance. It is affected by the possibility of finishing the operations in each stage within one period. If there were no precedence relationships between operations, there would be no need for sequential co-ordination between cells, because all operations could be performed independently. However, in general, precedence relationships are likely to appear between operations. There are three factors that influence the dependability of a product:

First, if successive operations that belong to different cells are allocated to the same stage, we face an increase in uncertainty due to the *organizational impact* of this decision, as we have discussed in former subsections. The complexity of co-ordination increases, and in order to avoid a low dependability we may insert some slack time. This can be accomplished by requiring a minimal time delay between operations that belong to different cells.

The second factor will be called the *longest-path orientation*. The allocation of operations to stages might lead to sequentially dependent operations in cells within a stage. The time required for completing a path of sequentially dependent operations may exceed the available time within a stage. This causes overtime work and tardiness, and hence a low dependability[6]. The likelihood of low dependability increases if allocating operations to stages generates longer paths of subsequent operations. Overlapping production can only partially solve this problem. The occurrence of such long paths within a stage reduces the possibility of developing stable standard sequences/schedules in the cells, which helps to achieve the benefits of PBC. Hence, a suitable allocation of operations to stages is one that allows enough slack time per stage to cope with the long paths caused by sequentially dependent operations within the stage.

Finally, dependability is also influenced by the timing of work load arrival at the bottleneck. This factor will be denoted as a *bottleneck orientation.* We can regulate the loading of a bottleneck with the allocation of operations to the stages. For example, 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 have illustrated this in Figure 4.6. The machine that performs operation *e* first had to wait until all preceding operations (*a*,*b*,*c*,*d*) were finished. In the alternative allocation shown in Figure 4.7, these preceding operations were completed within the preceding stage. At the start of a new period, the machine can immediately begin to process operation *e*, although the precedence structure of the product has not changed.

We want to stress that there is no need to strive for an equal distribution of work load over the stages, as is useful in the related problem of assembly line balancing. The differences between these problems make it useless to search for an equal distribution of work between the stages. Stage allocation influences the timing of the operations, not the total work load or utilization of the resources within the production system. It affects due date performance (dependability), speed of a specific product, and costs of the system. The allocation may result in an amount of overtime required to finish the work. The total number of working hours remains unchanged.

The above mentioned factors are demonstrated in a mathematical model in Appendix B. The mixed integer programming model consists of a longest-path orientation which can be extended with a bottleneck orientation. This supports the stage allocation decision.

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[6] Note that the length of these paths also influences the volume and mix flexibility of the system.

§ 4.4.5 Reconsidering the relationship between cells and stages

Literature on PBC stage design does not pay much attention to the stage allocation discussion. It assumes that cell boundaries are identical to stage boundaries. The negative consequences of such an allocation are usually ignored. In our opinion, the main reason for this lack of attention is the prevailing view on PBC as an intermittent production line without branches (see Figure 4.11).

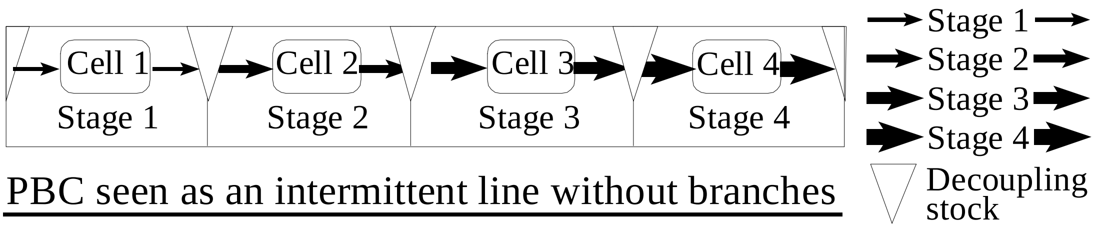

Figure 4.11 Traditional perspective on PBC synchronization

In Chapter Three, Section § 3.1.2, we discussed some of the similarities of the PBC single phase principle and this intermittent serial line system. These systems are only partly similar. PBC systems apply the synchronization mechanism of an intermittent production line for the co-ordination between the stages (the single phase principle), but not the physical layout characteristics and constraints of such a production line system.

In designing a line system, allocating the same type of operation to two separate stations offers no particular advantages. It could only be done either by duplication of machinery or by designing a special type of line layout (U-shaped line) that allows for machine sharing between the stations. The resulting investment costs or co-ordination costs make these solutions unattractive.

However, for PBC systems, such problems do not exist. The serial line system can be modelled according to the PBC definition of stages and the sequence of processing as shown in the left side in Figure 4.12. Each cell receives material from the stage in which it is active, just as we saw in Figure 4.11. The finished products are returned to the stage decoupling stock before the end of the period, but this stock does not need to be located in different locations. PBC controls the release of work to the cells, i.e., the arcs in Figure 4.11. A stage allocation that alows cells to be active in various stages has an impact on the way PBC operates. With such an allocation, the right side in Figure 4.12 would apply. At the start of a period, each cell receives input from different stages, and it has to process the input within one period. If all input is received at the start of a period, the cells operate still in a single phase system. PBC can perform this co-ordination, as it has only consequences for the release decision. If cells deliver each other within the same stage, they operate as in a multi phase system, which makes the co-ordination of the flows too complex for PBC.

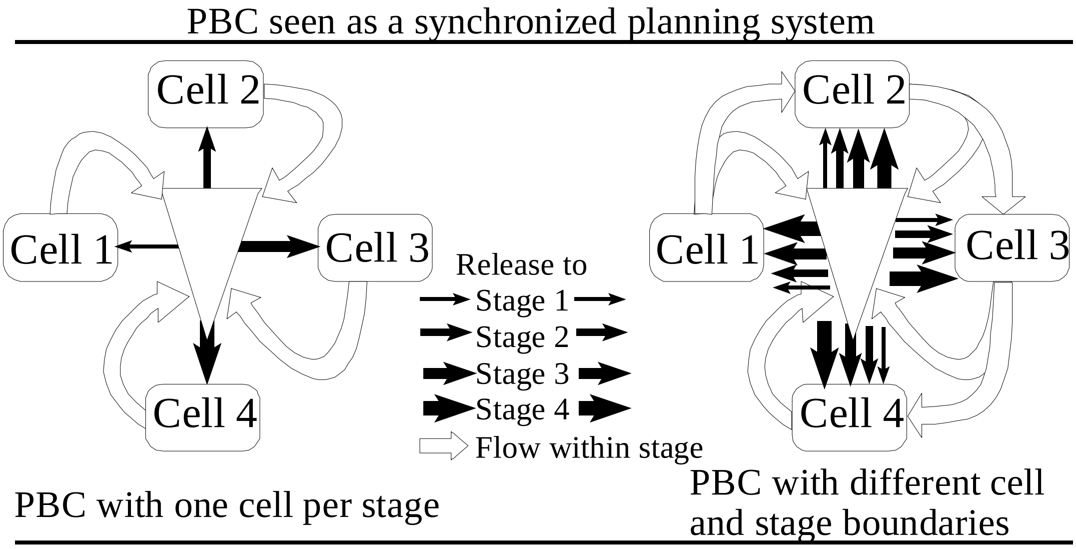

Figure 4.12 New perspectives on PBC synchronization

The right side in Figure 4.12 shows that the allocation of operations of a cell to separate stages creates no restriction to the material flow between the stages. The cell produces parts that are put in the stage decoupling or transition stock. At the start of a period, the cell is able to obtain all material that needs to be processed within this period from the transition stock. Only where another cell has to perform operations within the same stage in advance (a sequential relationship between the cells within the stage) will this material not necessarily be available at the start of the period, and production has to take place later during the period.

Stage definition in a PBC system is therefore primarily a decomposition of the material flow of the various products from a progress planning point of view. This should be distinguished from the decomposition of the production system itself, such as performed within a serial system. However, stage definition influences the effectiveness of the decomposition of a production system and at the same time, the decomposition of the production system will influence the effectiveness of the planning system structure.

§ 4.5 Summary and conclusions

For the design of a basic unicycle PBC planning system, two factors are very important: stage definition and period length determination. Stage definition has to do with deciding about the number of stages N and the contents of the stages (which operations to perform when). The contents of the stages affects the performance of the system with respect to flexibility, dependability, and costs. The period length P has to do with determining the planning frequency and hence the number of set-ups in the system. This has important consequences for operational issues relating to the production system, such as the *start/finish effect* and the *set-up time effect*. The number of stages N and the period length P together determine the manufacturing throughput time and the customer order lead time or forecast horizon. Relevant aspects of the planning system as well as the production system have to be taken into account when determining these factors, as the design of the planning system and the production system are interrelated. If the structure of the production system is designed without an understanding of an appropriate planning system structure, huge inefficiencies can result. The relationship between the design of a suitable structure for the production system and the design of the structure of the planning system is not unidirectional, as often is supposed in literature on production or planning system design. However, a good fit between the production system and the planning system is required to obtain short throughput times or achieve other system objectives. Reduction of throughput times cannot be achieved fully if only one of these systems is redesigned. Traditional approaches to planning system design, such as in MRP or Kanban literature, often apply a decomposition of the planning system that resembles the existing departmental, cell or work centre structure, without taking notice of the possibility of finding a better way to decompose the production system, one that takes account of the interaction between both systems.

In order to decompose the PBC planning system, we have looked at the stage definition according to processing stages that Burbidge uses in his Production Flow Analysis (PFA) method. We have shown that in PFA, the definition of the ‘set of parts’ controls the decomposition of the production system. The use of a processing stage decomposition can result in an improved interdepartmental flow. However, a processing stage definition is not directly suitable for finding the best way to decompose the planning system structure. The main reason for this is that the number of processing stages does not give any insight in the complexity of the co-ordination problem between and within the stages. A planning system should be able to adequately handle such complex co-ordination problems and needs to be structured such that this co-ordination can be performed.

With this in mind, we have developed a new framework for identifying the various choices that have to be made in order to determine an adequate structure of the planning system. The first step required within this framework is a formulation of the system objectives and a prioritization of them such that they can be used for guidance in designing the planning system. The various factors that play a role are speed (lead time), dependability (due date performance), flexibility, quality, and costs. However, the weight and priority given to these system objectives varies for each production situation. Therefore, a stage definition cannot be provided without a knowledge of these objectives and their ranking.

The main factors that we consider in our framework for PBC stage definition are related to changes in uncertainty and changes in the required accurateness of control. Both changes may lead to the introduction of a stage decoupling point between two successive processing steps.

The framework allows for stage definitions that involve the presence of multiple cells that are sequentially related within the same stage, as long as there is no substantial change in uncertainty or required accurateness of control. Valid reasons for involving various cells within one stage will be related to economic, group effectiveness, and environmental issues. The framework also allows for the occurrence of a cell in various stages. We have shown that the reduction in work in progress and dependability is a strong argument for choosing this solution, as well as the much smaller work load fluctuation within a cell. However, there are also reasons for not allowing cells to be active in several stages, as it leads to reduced standardization of period production requirements, unstable sequencing policy within cells, and an increased number of sequential relationships with other cells.

We have provided an approach for determining an allocation of operations to stages that takes into account the time/cost trade-off between several system objectives. This approach describes the effect of operation allocation on the length of the longest path within a stage and the effect on the arrival of work load at a bottleneck. The mathematical model is described in Appendix B and can be used to decide about a suitable allocation of operations to the stages.

Stage definition in a PBC system is primarily a decomposition of the material flow of the various products from a progress planning point of view. It determines *when* the operations are performed. This should be distinguished from the decomposition of the production system itself that determines where the operations are performed. The prevailing view on PBC stage definition is its similarity to an intermittent serial line system. PBC systems do apply the synchronization mechanism of such a production line for co-ordination between the stages (the single phase principle), but not the physical layout characteristics and constraints of such a production line system. PBC stage definition can facilitate the effectiveness of a cellular manufacturing system. At the same time, the decomposition of the production system influences the effectiveness of the planning system structure.