Chapter 8 Co-ordination between cells and PBC system design

PBC system design influences the required co-ordination between cells. PBC performs the overall co-ordination of the material flow through the logistic chain of the firm. The design of the PBC system determines the frequency of planning, progress control, forecasting. It also determines the horizon of planning and forecasting. Finally, it determines the contents of work orders that are released to the stages.

Not all necessary logistical co-ordination is being performed by PBC. First, the cells have to co-ordinate several activities that they have to perform in order to complete the work package that PBC releases to the floor at the start of a period. Second, co-ordination between cells within the same stage might also be required. If cells are sequentially or simultaneously related within the same stage, these relationships generate co-ordination requirements. PBC does not accomplish for this co-ordination.

The amount of co-ordination effort depends on the system objectives as well as the design of both the production and planning (PBC) system. We will call this *remaining* logistic co-ordination, in order to distinguish it from the co-ordination effort required for operating the PBC system, such as forecasting, information gathering, and periodic work order release.

Consequently, PBC system design results in a hierarchical decomposition of the planning and control system. The upper hierarchical level consists of decisions for the current execution period, as we have illustrated in Figure 3.9. Examples of these decisions are the determination of a sales plan for the first unplanned sales period (N periods ahead), the adaptation of capacity levels for intermediate stages, and the release of work orders for the current period.

The lower hierarchical level of the planning and control system consists of decisions regarding the remaining logistic co-ordination in the current period. These decisions concern both processes that are located within cells and between cells. The co-ordination effort at this level depends also on the design of the production and planning systems and the congruity of these designs. Production system design determines cell boundaries and planning system design determines stage boundaries, period length and number of stages. Chapters Four and Seven showed that these decisions are interrelated and jointly affect the amount of remaining co-ordination between cells at the lower hierarchical planning level.

This chapter studies the relationship between PBC system design and the co-ordination between cells at the lower hierarchical planning level. Section § 8.1 will examine the influence of PBC system design on uncertainty in a cellular manufacturing system. This uncertainty determines the remaining co-ordination requirements within and between cells. Section § 8.2 discusses the allocation of co-ordination tasks and responsibilities in the planning system and provides an architecture for stage co-ordination and its relationship with cellular control. Section § 8.3 summarizes our conclusions.

The chapter aims at providing further insight into the characteristics of the cellular decomposed production system and the consequences of PBC system design choices for the co-ordination between the cells.

§ 8.1 Effect of PBC system design on uncertainty in a cellular system

The central question in this section is to what extent PBC system design choices have an effect on the uncertainty in a cellular system. In order to answer this question, we will assume that the system objectives are known as well as the cellular structure of the production system. We are interested in the type of uncertainty that influences the possibility of reaching the desired mix of system objectives. Therefore, we will first explore the type of uncertainty that cells face.

§ 8.1.1 Uncertainty in cellular manufacturing systems

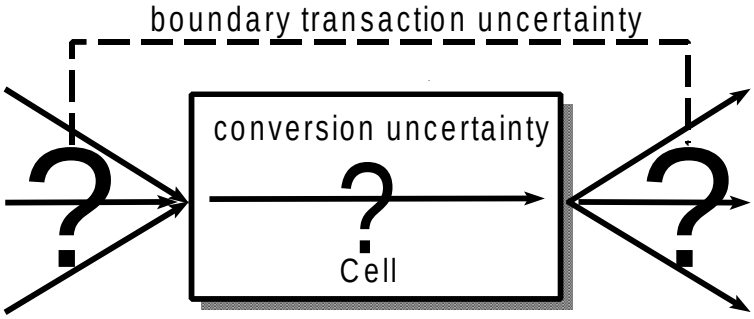

Figure 8.1 Uncertainty influencing remaining co-ordination in cellular manufacturing

Cells have to perform several activities in order to complete the work package that is being released from the PBC planning system. They need material, information, and instructions from other parts of the system in order to fulfil their task and complete the work package within a period. Hence, we see that cell performance depends on the availability of these inputs. Other parts of the system may demand outgoing flows of this cell. If these flows do not actually occur because the external party does not start moving the produced items, this may influence the performance of the cell. Susman (1976) introduced the term *boundary transaction uncertainty* to describe this type of uncertainty.

Boundary transaction uncertainty considers three facets of uncertainty in the relationship of a cell with other parts of the system. We call these facets Timing, Location, and Specification:

TIMING	WHEN	will incoming and outgoing (goods, resource, or information) flows cross the (cell) boundary?
LOCATION	WHERE	will these flows cross the (cell) boundary?
SPECIFICATION	WHAT	will be the specifications (quality and quantity) of the output?

If a cell would face no boundary transaction uncertainty that originates from relationships with its environment, it could still face uncertainty that influences its performance. This type of uncertainty is denoted as *conversion uncertainty*.

Conversion uncertainty concerns the way to deal with the required transformation *within* the cell. In addition to the timing, location, and specification of this transformation, uncertainty can exist on HOW the product has to be made and by WHOM. The selection of processing equipment, tools, operators, measurement methods, inspection procedures for inputs and output, and the determination of the sequence of activities that are required for the operation, influences the performance of the cell. Conversion uncertainty therefore considers how to convert these inputs into the desired output. The desired output not only refers to the product specification, but also to the system objectives cost, quality, speed, and so on.

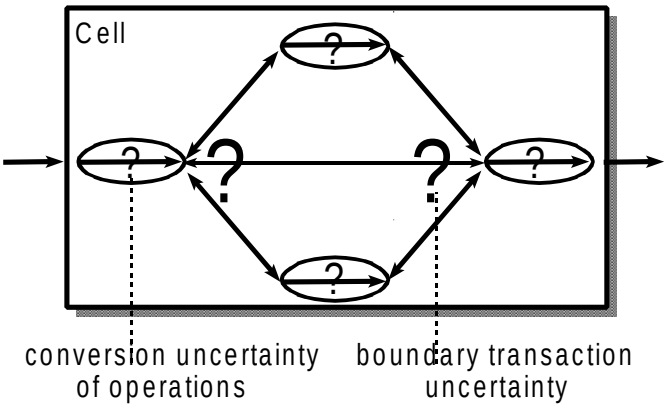

Figure 8.2 Uncertainty within cells

Figure 8.1 showed conversion uncertainty at cell level, where the cell is considered to be a black box. In Figure 8.2 we have opened the black box of the cell and again we find conversion uncertainty, which is now intrinsic to the required *operations* instead of the *complete transformation*, and boundary transaction uncertainty, now with respect to the availability of internal cell flows in order to perform these operations.

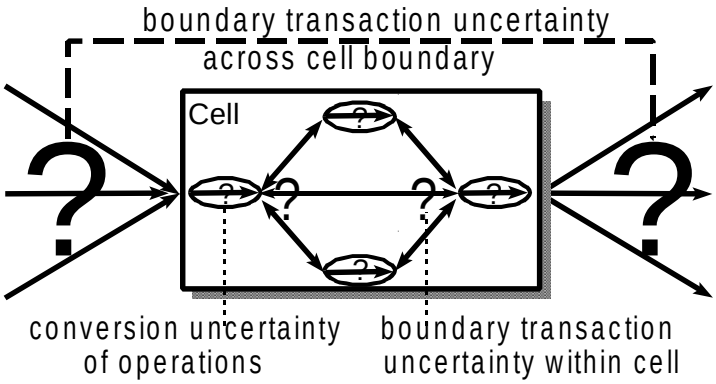

Figure 8.3 Three components of uncertainty in cellular manufacturing

We conclude that the source of uncertainty within cells can be decomposed into three components, as shown in Figure 8.3: boundary transaction uncertainty across the cell boundary, boundary transaction uncertainty within the cell, and conversion uncertainty with respect to the operations that have to be performed.

First, we will explore the effect of PBC system design on the conversion uncertainty and boundary transaction uncertainty *within* the cells. Sections § 8.1.2 and § 8.1.3 will pay attention to the effect of determining period length, number of stages and stage allocation on respectively this conversion and boundary transaction uncertainty.

Section § 8.1.4 will examine the effect of PBC system design on boundary transaction uncertainty across the cell boundary. There we will discuss the remaining co-ordination requirements *between* cells. It is necessary to examine both the co-ordination within and between cells in order to understand the consequences of changes in PBC system design choices. It considers both sequential and simultaneous relationships between cells and consequences of these relationships for the remaining co-ordination effort.

Section § 8.1.5 considers the ability to exploit latent relationships between cells for different PBC design choices. Finally, Section § 8.1.6 studies the relationship between the uncertainty in the system and the selected co-ordination mechanisms.

§ 8.1.2 Conversion uncertainty

The effect of PBC system design on conversion uncertainty within cells will be discussed separately for the three main choices in PBC system design: period length, number of stages, and stage allocation. In our conclusions on the effect of changes in one of these PBC system design choices, we assume that the mix of system objectives has not changed.

Period length

The length of the period has an important effect on the sources of conversion uncertainty. Susman (1976) already pointed towards the effect of a longer period when searching ways to cope with the inputs and to perform the transformation. He stated [1976: 96]: '*It is presumed that the longer the time available to organizational members to search for activities to convert input properties, the greater the likelihood that appropriate activities will become known to them*'. A longer period length clearly allows more time to determine a way to perform the transformation. Both in the preceding stages (preparing process plans in the ordering stage) and in the production period itself is more time available, which might lead to a reduction of conversion uncertainty.

However, shortening the period length might lead to the same result: a reduced conversion uncertainty. Shorter period lengths make it less necessary to introduce overlapping production, as we have shown in Chapter Six. Therefore, shorter periods make it easier to

allocate several successive operations (both production and preparatory tasks) to the same operator. Shorter periods might result in more variable and possibly longer work cycles for the operators, which eliminates one of the sources of conversion uncertainty, namely incomplete and erroneous specified work transfer. The reduced monotony of work might further lead to improved awareness of the characteristics of the task that is being performed, which again reduces conversion uncertainty.

Furthermore, shorter periods in combination with recurring (non-lumpy) demand results in an increase in repetition of work cycles. Repetition facilitates the process of continuously improving cell performance. This is a process of learning that obeys the general principles of learning processes as described in, for example, Senge (1990). We do expect advantages for the cells due to the application of more stable schedules and work patterns if repetition occurs. The schedule robustness allows a focussed effort to further reduce sources of conversion uncertainty that distort the desired system performance (e.g., costs, quality, and yield).

Concluding, we see that the length of period has a diffuse effect on conversion uncertainty within cells. If the repetition of product demand in the system is high (no lumpy demand in a basic unicycle PBC system), benefits of shorter period lengths with respect to a reduction of conversion uncertainty will probably exceed the benefits of longer period lengths. The latter will be more important in case of high demand variety and low repetition.

Number of stages

A higher number of stages reduces part of the conversion uncertainty. An increase in N increases the order throughput time. This gives more time to perform preparatory activities for operations that are delayed because of the increase in N. Part of the conversion uncertainty is therefore reduced. However, conversion uncertainty that is intrinsic to the resource that will be used for performing the operation is not influenced by a change in the number of stages.

Stage allocation

The allocation of operations to stages can exactly reflect the decomposition of the production system into cells. Such an allocation results in identical release and due dates for all work orders, where all operations that have to be performed within a cell belong to this work order.

If instead of this allocation, a situation arises with more cells being active in a stage (see Section § 4.4.2), some work orders may encounter smaller time windows in which the same operations have to be completed. This may restrict the search of the cell for the optimal mix of operator(s), tools, processing equipment, and so on, in order to perform such operations. We have discussed this extensively in Chapters Five and Six with our load oriented approach. Sequential relationships between cells within a stage restrict therefore the possibility to find the best way to perform the transformation process within a cell. In addition to the restricted availability of resources, material, and so on, within the smaller time window, we may also encounter a reduced search time for finding the best possible way of performing the

transformation during the period. Hence, stage allocations resulting in sequential relationships between cells in a stage cause an increase in conversion uncertainty within a cell.

If instead a reallocation of operations would be applied that results in a cell becoming active in more stages, we may encounter a reduction of sequential relationships between operations in a stage. If operations that were formerly performed within the same stage are allocated to different stages, this provides more degrees of freedom for the cell to schedule the various activities. As a result, we see a reduction of conversion uncertainty, because there are less restrictions on the timing of the activities within the period and hence more alternatives in the selection of processing equipment, and so on. Hence, a stage allocation that reduces sequential relationships between operations results in less conversion uncertainty.

§ 8.1.3 Boundary transaction uncertainty within cells

In this section, we will discuss the effect of varying the PBC system design parameters on the boundary transaction uncertainty within cells. We will assume that there is no boundary transaction uncertainty across the cell boundary. Note that boundary transaction uncertainty within the cell exists only if we encounter sequential relationships within a cell. These sequential relationships may concern material (i.e., goods flow between operations), tools, resources, or information. Hence, we assume that such relationships exist if we consider the effect of varying system parameters on this type of uncertainty.

In order to understand the causes for boundary transaction uncertainty, we have to make a distinction between the timing, location, and specification aspects. Causes for the timing facet (WHEN) of boundary transaction uncertainty can be identified by examining the queuing characteristics of the system. We distinguish between:

resource availability	the next processing step can only continue if the required resource has become available, which generally takes some waiting time because of the desired utilization of the resource
also known as	*congestion waiting time*
input flow availability	the next processing step can only continue if the last of all preceding incoming flows have become available
also known as	*assembly (or touringcar) waiting time, completion delay*
periodic service	the next processing step can only continue at specified moments in time and the input flows are generally present some safety time before this moment
also known as	*(train) platform waiting time*

The boundary uncertainty with respect to *resource availability* increases if we encounter higher utilization rates. The higher mean waiting times that are required in order to achieve higher utilization rates do in itself not result in an increase in uncertainty, but higher utilization rates also result in a higher variance of this waiting time (Bertrand, Wortmann, Wijngaard [1990a:178]. The higher variance results in less dependability towards the next processing step within the cell and therefore in higher boundary transaction uncertainty with respect to the timing facet.

Boundary transaction uncertainty with respect to *input flow availability* from preceding operations within the cell increases with the number of flows that have to be available before the next operation can start. The operation waits until the last input flow is available, hence its waiting time is a function of the maximum of the independent waiting times. The variability increases with an increase in the uncertainty in the independent waiting times, which again depends (among other things) on the utilization rates of resources that perform the operations.

Finally, we consider the effect of *periodic service* on boundary transaction uncertainty. An increase in the frequency of these services, for example transportation to the next operation, reduces the mean and variability of the waiting time and hence of the boundary transaction uncertainty between operations.

The location and specification facets of boundary transaction uncertainty play a less prominent role in cellular manufacturing systems compared with functional organized systems. The reason for this is the geographical closeness of successive operations, which results in less uncertainty on the location of materials, tools, and information. For the same reason, it is also easier to communicate on the required specification within a cell. These facets of boundary transaction uncertainty are therefore not primarily influenced by PBC system design decisions as long as a cellular system is used. In Section § 8.2, we will show that the allocation of responsibility for planning decisions in the system indirectly influences this type of uncertainty, but first, we will discuss the direct effect of varying the PBC system design parameters on the boundary transaction uncertainty within cells.

Period length

Increasing the period length results both in larger batches and in more time available for completing the set of work orders. For relatively short paths (time required for a sequence of operations), this increase will result in larger blocks of slack time, which reduces the boundary transaction uncertainty and simplifies the sequential co-ordination. For relatively long paths, it becomes more difficult to finish the whole batch within one period, as we have shown in the anomalous effects in Figure 6.6 and Figure 6.7. Therefore, an increase in the length of the period results in an increase in boundary transaction uncertainty for these work orders and hence a shift of co-ordination effort towards the work orders with longer paths. This same shift will occur for work orders with a higher probability of exceeding the due date, for example, because of high assembly waiting times. Within PBC, these orders should

receive priority over less urgent orders. Hence, increasing period lengths require an acceleration / retardation approach, as proposed by Van de Wakker (1993). Burbidge (1988) presents such a detailed co-ordination approach that schedules and controls critical operations closely during the whole period, while operations with more slack time receive less detailed co-ordination.

Number of stages

A higher number of stages increases the order throughput time, but does not result in a change in co-ordination requirements for boundary transaction uncertainty between operations, unless the allocation of operations to stages changes.

Stage allocation

Operations that have to be performed successively in the same cell can be allocated to different stages instead of the same stage. This results in a reduction of boundary transaction uncertainty between these operations. The next operation is safeguarded from the input flow availability waiting time, as the PBC system synchronizes these production activities. There is also less necessity to apply overlapping production if successive operations are allocated to different stages. The boundary transaction uncertainty that is caused by waiting time for periodic service therefore also diminishes.

§ 8.1.4 Boundary transaction uncertainty across cell boundaries

We will now focus on the effect of PBC system design choices on the boundary transaction uncertainty between cells. This type of uncertainty exists only if we encounter relationships between a cell and its environment. These relationships may concern material (goods flow), tools, resources, or information. Hence, we assume that such relationships exist if we consider the effect of varying system parameters on this type of uncertainty.

Co-ordination requirements across cell boundaries partly originate from the interdependency between cells, as there are also other elements in its environment. We will focus on the interdependency between cells. In Chapter Two, we introduced three types of relationships between cells: sequential, simultaneous, and latent relationships. From the three PBC system design choices, stage allocation causes sequential and simultaneous relationships to occur. We will therefore explore for these two relationships the influence of stage allocation on the boundary transaction uncertainty between cells. Latent relationships will be discussed separately in the next subsection. First will we discuss the effect of period length and number of stages on this type of uncertainty.

Period length

The length of period influences the boundary transaction uncertainty between cells. Each cell obtains all relevant information on the complete work order package at the start of the period. If the length of the period increases, the probability that this information is incorrect at the time of use increases. This might have consequences for the quality of decision making within the cell with respect to subcontracting operations, rerouting work to another machine, or hiring extra workers. Consequently, it might increase the boundary transaction uncertainty across the cell boundary.

Longer period lengths might make it easier to co-ordinate the use of shared resources by different cells. It becomes more easy to allocate several parts of the period for operations of cell I and other moments for cell II, because of the shift in co-ordination effort towards an acceleration/retardation approach that we have described in § 8.1.3. The work orders that require co-ordination that is more intensive can be treated separately.

Number of stages

Increasing the number of stages without reallocating the operations does not lead to a change in boundary transaction uncertainty between cells.

Stage allocation *stage allocation exactly reflecting the cellular decomposition*

If the stage decomposition exactly reflects the cellular decomposition (see the discussion in Section § 4.4), then all work orders that are released to the cell have identical release dates and due dates. The sequential relationships between cells will not concern the intercellular goods flows but only the intercellular flow of tools, resources, or information required to proceed with the transformation process. If there is no intercellular goods flow within a stage, the advantages for cell scheduling are mainly a reduced boundary transaction uncertainty:

- the cell faces less uncertainty with respect to the arrival of work orders
- the cell faces less uncertainty due to the fact that required departure times of work orders within the period do not vary
- the dependency of the internal schedule generation process from decisions of other cells is restricted to the planning of tools flow, resource flow, or information flow (again less boundary transaction uncertainty)

stage allocation resulting in simultaneous relationships between cells

Simultaneous relationships result in cells that perform in the same period activities for the same end product. The activities in itself are not related (for example, the production of a tool and the preparation of an accompanying direction for use), but both activities will be influenced by decisions concerning the order (e.g., cancellation). The internal co-ordination in the cell can benefit from the availability of information from the other cell on the progress of the order in determining priority between orders. Therefore, simultaneous relationships between cells within a stage influence the boundary transaction uncertainty between cells.

Cells can decide to allocate simultaneous related operations to different stages. The only change in uncertainty that we expect from this decision is a reduced sensitivity for mix variation, which causes a reduction of boundary transaction uncertainty between cells compared with an allocation of these operations to the same stage.

stage allocation resulting in sequential (goods flow) relationships between cells

If cells are sequentially interdependent within the same stage because of an intercellular goods flow, both cells face boundary transaction uncertainty. The first cell in sequence faces demand (output) uncertainty, while the last cell in sequence faces input uncertainty, as can be seen in Figure 8.4. The two sequentially interdependent cells in the same stage have to determine an internal transfer date of the work orders that have to be finished within the same period. If the PBC system should provide this sequential co-ordination, an operation reallocation would be required that might have consequences for other cells as well, leading to a shift in the interdependencies between cells.

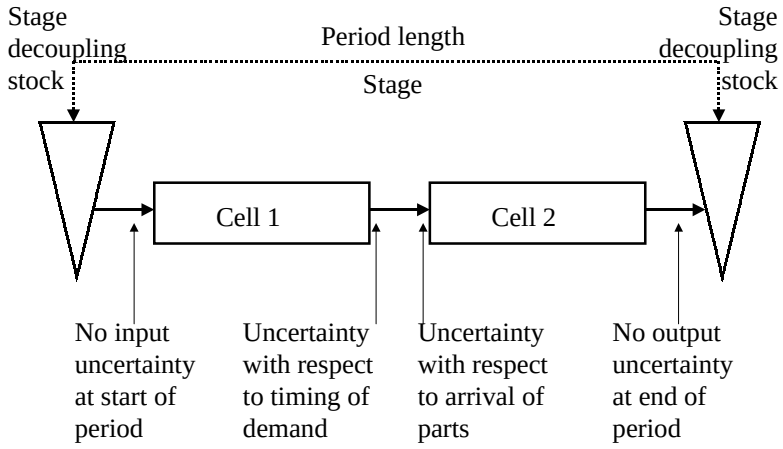

Figure 8.4 Uncertainty caused by sequential relationship between cells within stage

§ 8.1.5 PBC design and latent relationships between cells

A latent relationship between cells exists if flexibility is available in the production system that can be used to create or change a sequential or simultaneous relationship between cells. It describes opportunities of the system to change relationships between cells. PBC system design choices affect the possibility of the system to use these latent relationships.

Period length

If the period length increases, the PBC system loses control over the exact state of the production system. It cannot predict where problems will occur and hence it is more difficult to use the latent relationships between cells at program meetings when plans for the next period are being determined.

Number of stages

An increase in the number of stages increases the foresight of the planning system. If problems are foreseen with availability of capacity one or more periods ahead, an increase in N will result in either more preparatory time available, or more precise knowledge of the moments these problems will occur. Hence, an increase in N has effect on the possibility of using latent relationships between cells and developing alternatives for the typical sequential and simultaneous relationships between cells in the system.

Stage allocation

A different stage allocation also affects the use of latent relationships between cells. The timing of specific operations is influenced by this allocation and hence the use of resources within a period. The availability of alternatives for the selected resources during this restricted period depends on the allocation of these and other operations to the stages.

§ 8.1.6 Uncertainty and co-ordination requirements

PBC system design choices (determining P, N, and stage allocation) affect the uncertainty in a cellular manufacturing system.

A change in the length of period has a diffuse effect on the conversion uncertainty within cells. It depends on the degree of repetition of product demand if either reducing or increasing the period length reduces conversion uncertainty within cells. The boundary transaction uncertainty within cells shows the same diffuse pattern. Increasing the period length results in less boundary transaction uncertainty for work orders with short paths, but more transaction uncertainty for work orders with long paths. Therefore, a change in period length makes a shift in co-ordination requirements necessary in order to cope with boundary transaction uncertainty within the cells. The same holds true for the boundary transaction uncertainty between cells. In general, this transaction uncertainty increases with a higher period length

An increase in the number of stages might results in a decrease in conversion uncertainty, but does not influence boundary transaction uncertainty, neither within or between cells, unless the allocation of operations to the stages changes.

If the stage allocation resembles the cellular structure, we might encounter within a stage more sequential relationships between operations that have to be performed in the same cell and less sequential relationships between cells during a period. This allocation therefore results in relatively more conversion uncertainty and boundary transaction uncertainty within the cells and less boundary transaction uncertainty across the cell boundary. Alternative allocations might either result in more relationships between cells in a stage or more operations of a cell in different stages. The latter case results in the least uncertainty within

the system, as it introduces the largest amount of slack time within the product routings and lets PBC perform the required sequential co-ordination within the system.

We conclude that PBC system design affects the uncertainty within a cellular manufacturing system. In order to cope with the resulting uncertainty, we have to design appropriate co-ordination mechanisms. The design of the PBC system influences this process of designing co-ordination mechanisms as it decides on the nature, strength, and location of interdependency in the manufacturing system. It depends both on the desired mix of system objectives and on the possibility of applying specific co-ordination mechanisms between cells whether stage boundaries should reflect cell boundaries or preference should be given to alternative stage decompositions. Therefore, PBC system design clearly affects the co-ordination requirements between cells.

In the next section, we will explore the consequences of this distribution of uncertainty for the design of the planning system. As PBC will only be part of this total planning system, many of the co-ordination requirements in the cellular system have to be accomplished for at another part of the planning system. We introduce the notion of stage co-ordination to reflect this.

§ 8.2 Stage co-ordination as part of the planning system

PBC system design affects the distribution of uncertainty in the manufacturing system. The design can attempt to distribute uncertainty mainly within the cells and not between cells in a stage. For such a distribution of uncertainty in the system, we might prefer a high autonomy of cells. A high autonomy implicates the delegation of authority and responsibility with respect to decisions on the way to handle the uncertainty.

Alternative designs of the PBC system might result in different distributions of uncertainty. The decision about stage allocation can result in boundary transaction uncertainty between cells within a stage. This type of uncertainty need not diminish by creating relatively autonomous cells. Therefore, literature on socio-technical systems design (e.g., de Sitter, 1998, Kuipers & van Amelsvoort, 1990) incorrectly assumes that delegating authority and responsibility towards cells is necessary to reduce uncertainty and obtain the benefits of cellular manufacturing systems. Susman (1976) offers a more balanced view on this distribution of regulatory decisions in the planning system.

If we prefer a design of the PBC system that results in boundary transaction uncertainty between cells within a stage, we have to cope with the co-ordination requirements that result. The presence of sequential relationships between cells within a stage makes it necessary that the goods flow between the cells within a period has to be co-ordinated as well. The basic unicycle PBC planning system does not make a distinction between work orders that have to

be processed in only one or in several cells. The absence of support for the co-ordination between cells within a stage might lead to a reduction in the overall performance of the production system. This loss in performance is also indicated by Steudel & Desruelle [1992: 295]. Therefore, we will pay attention to the co-ordination between cells within a stage.

§ 8.2.1 Stage co-ordination

Stage co-ordination might provide the co-ordination requirements between cells during a period. In our simulation experiments in Chapter Six, we have tested a stage co-ordination policy (IDD) that uses intermediate due dates for work orders that visit more cells within a stage. The use of these intermediate internal due dates did not improve the dependability of the system. This may partly be due to the specific production structure of the simulated cellular manufacturing system. Hence, other stage co-ordination policies may perform better.

We have searched in literature on planning system design for an appropriate design of stage co-ordination. The framework of Bauer et al. (1991) introduces an intermediate hierarchical co-ordination level between the (MRP like) central planning system level and the decentral cell control level. They denote this new level as *factory co-ordination* and state that *'if the individual cells were autonomous, factory co-ordination would be unnecessary'* [1991:31]. However, in typical manufacturing plants '*the control task within factory co-ordination organizes the flow of products between all cells within a factory. The control task can be complex because of the various production constraints and manufacturing goals which relate to the entire manufacturing system. Issues such as delivery dates, work in progress levels, and utilization on capital intensive equipment, combined with manufacturing goals such as maintenance of high product quality and decreased product lead times too present a series of conflicting objectives which require trade-offs'* [1991:83]. The distinction that Bauer et al. make between the central planning system level and factory co-ordination is interesting. They do not offer a systematic treatment of the differences in planning decisions that have to be performed at these levels. Neither do they describe policies that can be applied at factory co-ordination level. From their description of factory co-ordination, we deduce that important facets of factory co-ordination are:

1 real time control within planning period (shorter reaction time than central planning)
2 context specific (relationships between cells that have to be co-ordinated are situation specific)
3 platform for mutual adjustment between cells in order to trade-off conflicting goals

If we look at this short list of facets of factory co-ordination, we see that these tasks generally belong to the task domain of a production planning function within an organization. The task domain of a planner that performs these tasks consists of the following:

First, the planning function transforms demands for end products into material requirements per period, orders new material, checks on the availability of capacity and input material, determines production orders and appropriate due dates for these orders. For these tasks, generally a central planning system is being used. These tasks belong to the *preparation of a plan.*

Next, the planning function is concerned with the *execution of this plan*. Work orders have to be released to the production system, the progress of the plan has to be supervised, problems that occur in the progress of the plan have to be identified, measures that might improve the progress of the plan have to be taken, and the mix of objectives for the production system with respect to this plan has to be communicated.

Takkenberg (1983) calls the second facet of the task domain of the planning function '*decision-making during the execution of a plan'* and he defines this control as: *'the supervision of the execution of the plan between two subsequent planning moments'* [1983:50]. The decision-making is directed towards obtaining the original planned objectives for the various system outputs. The plan is used as guidance in this decision making process. The mix of objectives reflects the trade-off that has been performed within the planning process and this mix should therefore be obtained within certain margins.

We can now return to the contents of factory co-ordination, as introduced by Bauer et al. (1991). In their view, the task domain at central planning level is restricted to the preparation of the plan. Note that this phase may include activities with respect to the ordering of material with suppliers, preparation of subcontracting, and so on. However, these activities are performed before work is released to the production system. The output of the central planning level is a list of work orders and their due dates. This is all comparable to PBC planning.

The translation of the central plan to the measures required for an adequate realization do not belong to the task domain of a production planner at central planning level. We denote the next co-ordination level as stage co-ordination[1]. It provides the remaining co-ordination between cells that are planned with a PBC system. The task domain of a planner at stage co-ordination level consists of what we have called the execution of the central plan. This execution has to be performed in accordance with the specific structure of the production system (e.g., degree of autonomy of cells). The contents of the control efforts cannot be determined in advance, but depends on the situation that occurs within a period. The loading and capacity of the cells varies per period. Loading variations may for example be caused by yielding problems, demand variations, lot sizing decisions, and so on. Capacity variations may be caused by, e.g., illness of work force, or maintenance of resources. Furthermore, the

[1] Stage co-ordination is not identical to factory co-ordination as presented in Bauer et al (1991). Stage co-ordination does not distinguish a production environment design task at this layer of control, and gives more attention to the co-ordination requirements due to the stage decomposition of PBC.

PBC plan may require the use of transfer batches between cells. These circumstances ask for specific measures with respect to the co-ordination between cells. Stage co-ordination has to provide this facet of central planning.

The task of stage co-ordination may well be performed without allocating formal decision authority to one planner. A stage co-ordination planner might function appropriately at a liaison position between the cell controllers, as the effectiveness of the co-ordination is based on sharing information between the various cell controllers and the central planning. Formal decision authority at one central position does not guarantee a high quality of the decisions.

Stage co-ordination may still be required if stage boundaries exactly reflect cell boundaries. Adjustment mechanisms for the central plan may be required even if there are no planned material flows between cells within a planning period. We can still face latent relationships, uncertainty, unexpected circumstances, and resource or information flows between cells that may require co-ordination and supervision. Only in case of purely autonomous cells, such co-ordination is superfluous, as indicated in the citation from Bauer et al [1991:31].

We conclude that the distinction between a central planning level, a central stage co-ordination level and a decentral cell control level can be useful, although we want to stress that the distinction between both central (or upper) hierarchical levels is somewhat artificial.

§ 8.2.2 Functional architecture of stage co-ordination within PBC planning

The decomposition of the total planning and co-ordination task in these three task domains has important consequences for the performance of the total system. We agree with Habich [1990:39] who states *'Die Aufgabe der zentralen Systementscheidungskoordination besteht darin, einzelne, kundenbezogene Fertgungsaufträge fertigungs- und montagegerecht zu synchronisieren und in der Gesamtzielsetzung entsprechende Inselaufträge zu dekomponieren'*. In case of relatively autonomous cells, the detailed scheduling decisions with respect to the work orders in the cells are often decentralized. A cell scheduler decides on the time at which a work order is processed at a machine within the cell. He is only responsible for completing the work order package of his cell within time and other budget constraints. If there are cells that are sequentially interdependent within a stage, the local optima that will result from these decentralizations have to be managed such that the overall performance is according to plan. This is where stage co-ordination becomes important.

Three functions are seen as belonging to the task domain of stage co-ordination. These functions are described in the functional architecture in Figure 8.5:

1 determining intermediate release and due dates for work orders
2 enabling transfer of material (transfer batches) between cells
3 redirecting material, resource, and information flows between cells

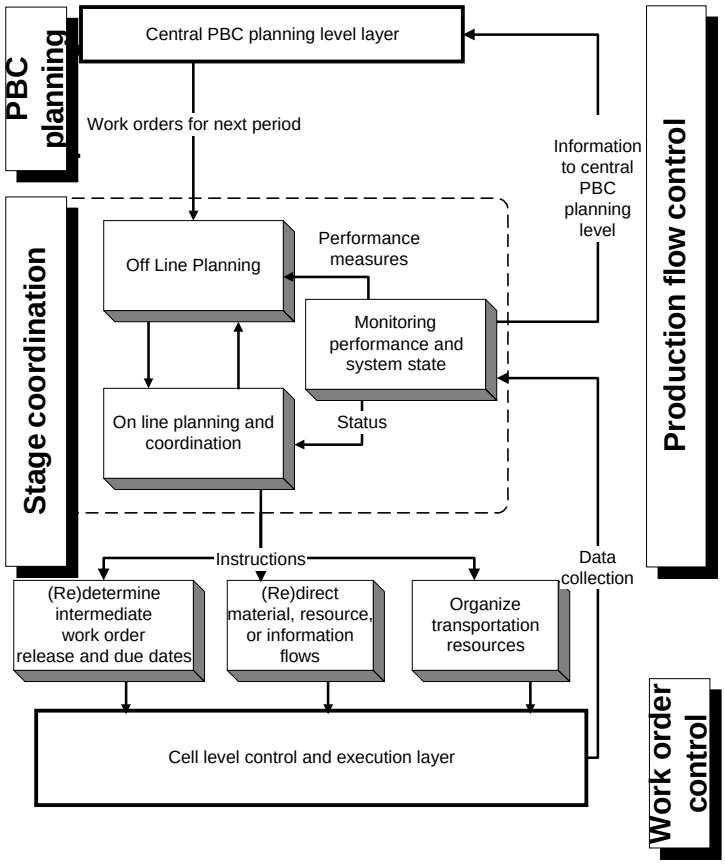

Figure 8.5 Functional architecture of stage co-ordination level

Within stage co-ordination, we can distinguish between off-line planning activities, on-line decision making and implementation, and monitoring both performance and system state.

The off-line planning task develops off-line plans for the current PBC planning period. This plan may be used to determine realistic intermediate release and due dates for the work orders released from the PBC planning level. The plan can further be used to extract information on the required transportation resources for between cell flows of transfer batches. It depends on the stage decomposition, on the length of the period, but also on the system objectives and the autonomy of the cells if such an off-line plan has to be made and how it is used. The IDD stage co-ordination policy that we used in our simulation study might have been not the most appropriate given the distribution of uncertainty within the system. The intermediate due dates that result from the stage co-ordination policy can be used to perform several necessary preparations, such as the arrangement of transportation equipment in order to deliver material to other parts in the system, without affecting the autonomy of cells.

The on-line tasks relate to all required co-ordination activities with cell controllers, the provision of instructions with respect to the organization of transportation resources, and the redirection of flows between cells. These tasks involve the communication of the expected release and due dates to cell controllers. Cells that propagate local solutions that make it

impossible for other cells to realise their goals can be amended at stage co-ordination level through a change in the release and due dates within the planning period. This influences the decisions at cell level. A relationship from on-line planning to off-line planning is needed. Finally, monitoring notifies the behaviour of the system and checks on circumstances that may require control efforts in order to enable the execution of the original plan.

§ 8.2.3 Examples of stage co-ordination

The case studies that we have performed show some examples of stage co-ordination, although they do not use a PBC system. However, they encounter relationships between cells and we have shown in Section § 2.3 that cases choose to co-ordinate some of these relationships without intermediate intervention of the central planning system. The sequential relationships between a prefabrication cell and a fabrication cell, between two fabrication cells, and between a fabrication cell and a finishing cell were sometimes co-ordinated by a type of stage co-ordination. We also identified that Case IV did not apply stage co-ordination for the sequential relationship between cells in the same stage, causing a low dependability.

Literature provides also some interesting examples of stage co-ordination. Dale and Russell (1983) report on a firm that introduced *shop loading analysts* in order to bridge the gap between overall production plans and cell supervisors, who have to meet the plans, whether possible or not. The company believed that if cell supervisors were given too high workloads and too short due dates, they would eventually return to ‘functional’ thinking with a totally unplanned transfer of labour and material between cells. The shop loading analysts were given the following tasks and responsibilities:

1 Translate the central plan for this period into realistic workloads for each of the cells.
- Capacity related factors such as material, manpower, and machine availability, expected excess work (modification and rectification) had to be considered.
- Intermediate release and due dates had to be determined for work orders that required assembly within the same period. They had to liaison with the monitoring function for co-ordination of the resulting *simultaneous relationships* between cells *within* the stage.

2 Negotiate with central production planning on desired modifications in the central plan (more/less work for underloaded or overloaded resources).
3 Make specific subcontract and group reallocation recommendations based on the expected loading for at least five planning periods ahead in time.
4 Analyse the variations from the central plan in the last planning period and identify relevant reasons for these variations and enable adequate monitoring.

Greene and Sadowski (1983, 1986) addressed the need for stage co-ordination in a cellular system. They describe a situation where the allocation of a work order to a cell had still to be performed at stage co-ordination level. The central planning level only determined that there would be sufficient capacity to perform the operation. The allocation of the work order to a cell was based on the loading patterns of the cells.

§ 8.2.4 Final remarks

We conclude from this analysis, that co-ordination between cells within a stage can be performed at a central stage co-ordination level if the achievement of system objectives necessitates improved planning and control compared with the co-ordination provided by a basic unicycle PBC system. The type of co-ordination mechanism that should be applied depends on the configuration of the PBC system. If stage decomposition within PBC resembles the cellular structure of the production system, less sequential co-ordination has to be performed at stage co-ordination level. The co-ordination of other relationships between cells may still be necessary. We distinguish three functions at stage co-ordination level: determining intermediate release and due dates for work orders, enabling transfer of subbatches between cells, and redirecting material, resource, and information flows between cells. We have provided a functional architecture for stage co-ordination that consists of an off-line planning for the current period, on-line planning and co-ordination activities for between-cell control, and finally, monitoring performance and system state.

§ 8.3 Conclusions

PBC system design choices affect the distribution of uncertainty in a cellular manufacturing system. A change in the length of period influences both the conversion uncertainty within the cell and boundary transaction uncertainty between cells. A change in the number of stages might results in a change in conversion uncertainty, but does not influence boundary transaction uncertainty, neither within nor between cells. Changes in the allocation of operations to the stages most importantly affect the distribution of uncertainty within and between the cells. If the allocation results in more cells becoming sequentially related within a stage, conversion uncertainty and boundary transaction uncertainty between the cells increase. If the allocation results in more operations of a cell being performed in successive stages, conversion uncertainty and boundary transaction uncertainty within the cell decrease.

In order to cope with the distribution of uncertainty that results from PBC design, appropriate co-ordination mechanisms should be used. We have argued that allocating regulatory decision authority to cells is not sufficient for all possible distributions of uncertainty. Especially in case of sequential relationships between cells, we need an intermediate co-ordination level between central PBC goods flow planning and decentral (local) cell planning. We introduced the notion of stage co-ordination and provided a functional architecture of this co-ordination level. Stage co-ordination should determine intermediate release and due dates for work orders, enable the transfer of material between cells, redirect material, resource, and information flows between cells when necessary, and monitor performance. We distinguish between off-line planning activities, on-line decision making and implementation, and monitoring. The necessity of stage co-ordination does not imply a specific distribution of authority within the system. It may be provided by a planner or by cell foremen.