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Riezebos, J.; Gaalman, G.J.C.

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RELATIONS BETWEEN CELLS IN CELLULAR MANUFACTURING

J. Riezebos and G.J.C. Gaalman

SOM theme A: Structure, Control and Organization of Primary Processes

Abstract

This paper analyses the kind of coordination that is necessary in firms that use cellular manufacturing in producing parts. We distinguish two levels of coordination: internal and external. The coordination at these levels is further divided into primary and secondary coordination. In this study we concentrate on coordination requirements between cells with respect to the primary transformation process, i.e. the external primary coordination within cellular manufacturing. We present reasons from the literature for the existence of various relations between cells. A comprehensive description of the external primary coordination requirements is offered in three types of relations between cells: sequential, simultaneous, and latent relations. We show that using this distinction helps to identify specific coordination requirements between cells in the five firms we studied.

Keywords

Cellular Manufacturing; Coordination; Parts Production; Group Technology

1. Introduction

In mechanical parts production, many firms have changed to cellular manufacturing without fundamentally changing their production planning and control systems. They are often facing problems with the support given by these systems. Wildemann [1] noted that 56% of the firms that had adopted segmentation of their production system had not significantly modified their method of planning and controlling the production system. This is remarkable, as many of the expected benefits of a change to cellular manufacturing are logistical in nature. One would expect that logistical benefits such as short throughput times and high delivery performance can be achieved more easily if also changes are made to the production planning and control system.

In this paper we analyse the kind of coordination between and within cells that is necessary in cellular manufacture. We present the results of five short case studies performed in firms that use cellular manufacturing in their small batch production of mechanical parts.

The paper is organized as follows. It starts with a short characterization of the production situation in small batch mechanical parts producing firms. We discuss the type of cellular manufacturing system that can be applied in the production of parts and the benefits that are generally expected from this way of organizing the production. Next, we analyse the type of coordination within cellular manufacturing by introducing two levels of coordination: internal and external, and two objects of coordination: primary and secondary. The rest of the paper focuses on the external primary coordination level. We present an overview of the literature on the use of relations between cells and conclude with a comprehensive description of external primary coordination requirements by introducing three types of relations between cells: sequential, simultaneous, and latent relations. These relations between cells are worked out in the remaining part of the paper. We introduce the five short cases and show the differences in the presence of the sequential, simultaneous, and latent relations and in the way they are coped with. We end with conclusions on the usefulness of this distinction.

2. Parts production and cellular manufacturing

The characteristics of producing mechanical parts in small batches can be described in terms of operations performed, resources used and orders produced.

The types of operations can be distinguished in material-preparation operations, machining operations, sheet metal operations, welding operations, and finishing operations. For the production of complex composite parts some assembly operations may be needed. Finally, measuring operations and transportation activities have to take place. The material that is processed can differ in type (metal such as ferro, non-ferro and cast-iron, fibreglass, or synthetic material) and in shape (product-specific castings or bar stock, such as sheet, staff, or cubic-shaped material).

The resources that are used in producing the parts are processing and measuring machines, human operators, cutting tools, fixtures, product carriers, and transportation equipment. The resources are typically not dedicated to one product. Therefore, alternatives exist in the combination of resources needed to produce a specific part. To start producing an order, all required resources have to be available at the correct location. This often results in flows of resources within the system. Besides these resources, information is needed, such as processing and measuring instructions, which can be interpreted by operators or machines, and planning data that can be used in controlling the system.

Generally, there is a high variety in the mix of orders produced each period. The degree of repetitiveness of an order of parts differs per product and per firm. Order sizes are often small, and parts are typically not made to stock.

Small batch parts manufacturing firms traditionally use a functionally organized production system, but in the last decades the interest in using cellular manufacturing has grown. In a functionally organized production system the departments are specialized in performing one operation, e.g., drilling, milling or bowing. However, specialization can also take place according to the degree of automation applied in processing the parts.

Firms that have adopted cellular manufacturing have changed their production system such that it consists of several cells that can perform a set of different operations. The extent of this set of operations can vary per cell. The type of

layout applied within a cell ranges from dedicated cells with a kind of flow line to hybrid cells with a functional layout within the cell. Firms that apply cells in their small batch parts production use mostly hybrid cells.

According to Burbidge [2], the main benefits that can be expected from a change towards cellular manufacturing are substantial reductions in material throughput times and material handling, improvements in quality and accountability, better trained workers, higher job satisfaction, and a production system that is better prepared for future process automation. Other benefits that are often mentioned are higher delivery performance, lower work in progress, and a higher volume and mix flexibility. It should be noted that many reported benefits can only be achieved when also changes are made to other parts of the production system, e.g., the production control system or the way production engineering operates.

3. Coordination within cellular manufacturing

A production system can generally be decomposed into several relatively independent units. The coordination requirements of such a unit can be assigned to two levels: internal and external coordination. Internal coordination concerns all coordinating activities that can be performed within a unit without tuning up with elements outside the unit. External coordination requires this outward orientation.

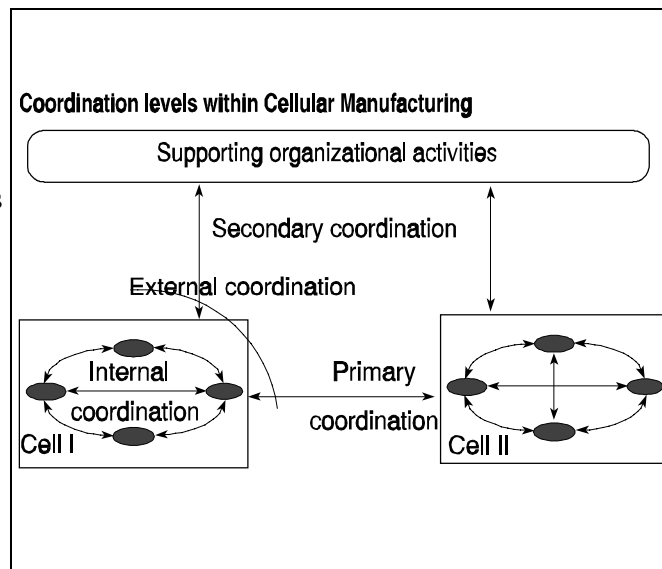


Fig. 1 Coordination with and within cells

At each level coordination can further be divided into *primary* and *secondary* coordination. Primary coordination concerns the coordination necessary to

proceed with the primary transformation process of the production system¹, while secondary coordination involves all coordination needed to support this process. Figure 1 illustrates this distinction for the coordination issue within cellular manufacturing.

In this study we focus on the external primary coordination within cellular manufacturing. External primary coordination concerns not only the coordination of the flow of orders between the cells, but also the coordination of resource and information flows that are necessary to maintain this flow of orders, for example cutting tools, measurement tools, human operators or NC programs. It can be distinguished from external secondary coordination. The latter is required if another part of the organization places a demand on the capacity of the cell complimentary to the primary activities of that cell. Therefore, secondary coordination does not concern the primary activities of the cell, but it does have consequences for these activities.

Coordination requirements have to be distributed over the two coordination levels. This concerns, among other things, the assignment of tasks and responsibilities to the cells and the design of the boundaries of the cells. The distribution of coordination requirements over the levels need not result in the same set of coordination requirements for all cells in the production system. It is possible to let certain cells specialize in handling specific coordination requirements, such that there is no need for other cells to coordinate on that aspect. An example of this is a cell that always has to be approached if design modifications or new products are to be introduced. All external secondary coordination requirements with research and development, including the involvement in concurrent engineering processes, are handled by this cell, and the other cells are shielded from this type of coordination requirement. This we call specialization of coordination requirements.

The distribution and specialization of the coordination requirements over both

¹ The primary transformation process of the production system consists of all transformation activities that are required to fulfill the demands that are placed on the system by the accepted customer orders.

the coordination levels and the different cells have consequences for the selection of coordination mechanisms. The appropriateness of planning as a coordination mechanism within cellular manufacturing depends on the outcomes of this process.

In this section we introduced two coordination levels and discussed two objects of this coordination within cellular manufacturing. In the next sections we focus on the external primary coordination level and give attention to the relations between cells that cause these requirements. First, an overview of the literature on this subject is presented and discussed. Next, we define three types of relations between cells that can be used to give a more comprehensive description of the relations between cells in practice.

4. Literature on relations between cells

Much of the literature on the design of cellular manufacturing systems stresses the importance of avoiding intercell movement of intermediate products as much as possible (see, e.g., Garza and Smunt [3], and Chow and Hawaleshka [4]). For example, Garza and Smunt stated that the main benefits of dedication are lost if intercell flow of material is allowed. This type of literature assumes that cells are dedicated to the production of a fixed product family. However, the benefits of cellular manufacturing are not restricted towards the reduced flow of material between cells. Cells that combine different resources are therefore not necessarily dedicated to a fixed product family.

Alford [5] worked this out and distinguished between cells that are dedicated to a fixed product family, getting the disposal of the required resources, and cells that are dedicated to a fixed combination of different operations that can be performed, getting the disposal of products that need (part of) this set of operations. This distinction becomes visible if the design of one of the products allocated to the cell is changed such that a new type of operation is required. If this new operation is added to the cell, the product family of this cell remains the same. If the product has to visit another cell for the new operation, the set of operations allocated to the cell remains the same. In the latter type of cell, the benefits of dedication are not expected from the resulting flows within the

system, but from the combinations of operations and hence resources in the cells. This makes the existence of material flows between these cells less inconvenient.

Burbidge [6] distinguished between *cross flow* and *back flow* relations between cells and used the notion of processing stages in describing these flows. He considered four stages: prefabrication (material production), fabrication (component processing), finishing (painting) and assembly. We interpret a cross flow as a relation due to the flow of material between cells at the same processing stage, and a back flow as a flow of material from a cell to a preceding cell in the processing stage sequence, opposite to the main flow of material, that follows the direction of the processing stages.

Burbidge stated that if cross flow relations are allowed between cells, throughput times, stocks and handling costs will be increased, quality control will be more difficult, and it will be impossible to hold the cell foreman responsible for quality, cost, and completion by due date.

However, several reasons can exist to accept cross flow relations or even back flow relations between cells, at least temporary. Burbidge mentioned three reasons: support a quick change to group technology, design modifications, and introduction of new products. Less acceptable, according to him, are capacity-related reasons, e.g., performing elsewhere intermediate operations instead of investing in the necessary machines and performing the operations within the cell.

Rolstadås [7] noted that, due to practical adaptations, preparatory or supplementary operations will often be performed outside the cell. He distinguished three classes of parts: those completely manufactured in one cell, those needing operations outside the cell on single machines, and those needing to be processed in another cell. The existence of the latter two classes results in material flow relations between cells.

The literature mentioned so far described the existence of intercell relations due to the required flow of material, which leads to external primary coordination requirements. The importance of this type of coordination requirements can also be concluded from the work of Alford [5], who compared a number of surveys on cellular manufacturing and concluded that cells cannot often be effectively

isolated from other parts of the factory. She even raised the question on the actual effectiveness of aiming this: cells seem to be necessarily parts of networks.

The variety in relations between cells that belong to the same system is also noted by Dale and Russell [8]. In their report on a redesign of a machine shop they introduced simple cells and complex cells and distinguished these cells in the type of material flow relations with other cells. The simple cells were placed in line such that only simple material flow relations between these cells remained. These cells and relations could be controlled using a simple coordination mechanism directed to obtaining the benefits of cellular manufacturing. The complex cells were designed such that interchange of work from one cell to another was possible, leading to more complex material flow relations between the cells. By the interchange of work orders between these cells, queues of parts were balanced and fluctuations in market demand could be met. So the complex cells had a high mix flexibility due to the usage of relations with other cells in planning the production. In this way short throughput times could be guaranteed while producing with an acceptable utilization rate during the year.

This type of relation is further analysed by Willey and Ang [9], who showed that changes in part mix and volume can result in an imbalance in workloads between and within cells. In situations where production cells are not completely disjoint these problems can be mitigated by transferring workloads between cells, so they used these relations between cells in the control of the production. They tested several heuristics and the results of their simulation experiments showed that the decision when and to which alternate machine centre workloads are being transferred can have significant influence on shop performance.

We conclude from these two studies that it can be highly efficient and attractive to use this type of relation between cells in the planning and control system. The possibility of using this type of relation between cells generates external primary coordination requirements in the system. The required coordination does not only concern the control of the flow of material between the cells, but also the decision when and to which cell the transfer of workload

has to take place.

In the extensive literature on the comparison of cellular manufacturing systems and functional production systems also attention is given to the relations between the machine groups. Suresh and Meredith [10] described the trade off between the loss of pooling synergy if cellular manufacturing is used, and the possibilities of reducing set up times, lot sizes and applying part-family- oriented scheduling rules. The loss of pooling synergy is caused by the applied partitioning of the production system in cells. This partitioning constrains the distribution of orders (i.e. the direction of the material flows) over the available capacity in the system. They gave no attention to other flows that appear in a production system, such as resource flows, neither to the possible redistribution of partly complete orders (and hence redirecting material flows) after the initial assignment. Rathmill and Leonard [11] performed a comparable analysis, and they stated that comparisons with functional production must occur at total resource level, not at machine group level. With this statement they emphasized to take into account factors such as relations between cells due to resource usage and resource availability.

From this literature survey we conclude that there are several good reasons for the existence of flows between cells, especially if these cells are dedicated to a fixed combination of operations that can be performed (Alford [5]). Furthermore, the type of relation between cells that exists due to the possible interchange of work has also to be considered, as they can be used in a planning system to improve shop performance. So the external primary coordination requirements do not only concern the coordination of material flow relations, but also other types of flows between cells as well as the available flexibility between cells. Although the importance of considering other types of relations is recognized in the literature, no comprehensive description of the existing relations between cells is available. This often brings about a too restricted view of the required coordination effort in cellular manufacturing within the literature. In the next section we fill this gap and present a categorization of relations between cells by introducing three types of relations between cells.

5. *Sequential, simultaneous and latent relations between cells*

External primary coordination was defined as the coordination between cells necessary to proceed with the primary transformation process of the production system. Therefore, the presence of orders in the system can induce this type of coordination requirement by creating relations between cells. Determination of the type of relation provides information on the extent of the primary coordination requirement between these cells. This can aid in the decision to meet this coordination requirement and subsequently in the selection of an appropriate coordination mechanism, for example planning or mutual adjustment.

External primary coordination requirements can exist with respect to three types of relations between cells: sequential, simultaneous, and latent. In this section we first introduce these relations formally and afterwards we work them out.

◆ A **sequential relation** between two cells exists if a flow and a corresponding sequence between the cells is prescribed that is needed to proceed with the primary transformation process of the system. This sequence has to be prescribed by a plan; this may be either a process plan or an order that has to be produced or a production (allocation) plan. We distinguish between sequential relations due to the existence of:

- 1) a prescribed *material* flow between cells (due to the specification and allocation of operations), further divided in:
 - material flow according to the main goods flow over the processing stages;
 - incidental or structural intercell material flow that deviates from this main flow;
- 2) a prescribed *resource* flow between cells;
- 3) a prescribed *information* flow between cells.

◆ A **simultaneous relation** between two cells exists if a parallel connection between particular activities that have been allocated to these cells is prescribed and needed to proceed with the primary transformation process of the system. The existence of this relation also results from a process plan or from the production (allocation) plan.

◆ A **latent relation** between two cells exists if a sequential or simultaneous relation between the cells can be created or changed by using the available flexibility in assigning operations, resources, material, or information to both cells. The relation between both cells is labeled latent if:

- 1) prescription of the flow between these cells or of the parallel connection between these cells has not yet been done or completed, but is taken in consideration; this is the case with incomplete specification (process plan) or allocation (production plan) of the required operations, resources, material and information to the cells;
- 2) an alternative in the already prescribed flow or connection between both cells is present with respect to this specification and allocation of operations, resources, material and information; the next two types of alternatives cause a latent relation between the cells:
 - existence of an *alternative cell* that can be involved in the specification or allocation plan; the cells are related because the alternative cell can also perform the required operation, or use the same resource, material or information to proceed with its primary process;
 - existence of an *alternative sequence* in which the cells either are visited to perform the required operation or will have the disposal of the resource, material or information.

The existence of the above-mentioned relations depends on the orders that are to be produced. An order is seen as the most comprehensive set of specified requirements of one (internal or external) customer to be met by the system, where the specifications include the type of products and the amount, quality and delivery aspects. The set of accepted orders causes the relations between cells. Relevant characteristics of these orders are used to determine possible specifications and allocations of the corresponding operations to the cells. This results in a set of generic process plans and an aggregate production (allocation) plan. The information contained in these plans is sufficient to determine between what cells relations will exist. The type of relation can still vary.

We have labeled them as latent relations as far as the existence or direction of a flow or a parallel connection between the cells has not yet been determined.

The extent of the external primary coordination requirement that results from the existence of these latent relations concerns the tuning of capacity requirements and capacity availability without knowledge of certain specific flows and connections that will appear between the cells at the time of producing the order.

To take a decision on the specification and allocation of operations to the cells is a way to cope with these external primary coordination requirements. However, the use of this kind of planning as a coordination mechanism generates another type of relation between the cells (sequential or simultaneous) and accordingly another extent of the external primary coordination requirements. The use of planning helps to avoid certain possible conflicts in the use of resources, material or information, but the chosen specification and allocation have to be monitored and probably updated if the state of the production system changes. Besides, the resulting flows in the system have to be controlled.

Note that for determining the type of relation the production plan need not contain information on the timing of the activities, e.g., the periods in which the distinguished flows will appear or the activities performed. Information on the specification and allocation of operations, resources, material and information is needed to determine if latent relations and simultaneous relations will exist. Knowledge of the sequencing of the operations, resources, material and information is required to determine if sequential relations between cells will result. In the remaining part of this section we will further explain the types of relations that were introduced.

Sequential material flow relations are distinguished into relations caused by the segmentation of the main goods flow (e.g., the boundaries between cells that exist due to the differences in processing stages), and incidental or structural deviations from this flow. This distinction is important from a coordination point of view, as it can have impact for the way the corresponding primary coordination requirements are coped with. Incidental or structural intercell movements that deviate from the main goods flow are easily identifiable in a cellular manufacturing system. These intercell movements are between machines or cells at the same or a former processing stage. In a cellular manufacturing

system, the percentage orders that need such intercell movements are generally small compared with the total number of orders processed. This makes it possible to coordinate the flow of orders that need such intercell movement with another coordination mechanism then used for coordinating the main flow.

The second type of sequential relation originates from the intercell flow of resources necessary to proceed with the primary process of the production system. If it is prescribed that a cell has to have the disposal of a specific resource for use in its transformation process, and this resource is first used in another cell, there exists a sequential relationship between these cells. Examples of such resources are cutting tools, fixtures, transportation equipment, but also human operators that have to be interchanged between the cells.

The last type of sequential relation that we consider is a relation between two cells due to the prescribed delivery of information from one cell to another. If this information is not given to the cell, it cannot proceed with the primary activities that have to be performed. So these cells are sequentially dependent in the primary process. It is important to distinguish information flows needed due to this sequence dependency and information flows needed for controlling the primary process. Only the first type is considered here and it includes such information as order documents, processing and measuring instructions (e.g., NC programs), measurement reports, etc. The flow of this information will be often combined with either the flow of material from one cell to another, or the flow of resources between both cells. In that case no new relations between the cells result, although the information flow does generate a coordination requirement. However, the flow of information need not be combined with one of the other flows; it can generate a sequential relation between cells on its own and hence create a specific coordination requirement.

Concluding, we want to stress that two cells can have a sequential relation while never delivering material to each other; flows of resources and information also generate sequential relations. Investigation of the prescribed flows between cells is worthwhile as it helps to describe the extent of external primary coordination requirements.

Simultaneous relations can be encountered if two cells perform activities for the same order. The activities are connected due to the convergent structure of the complete process plan of the order. An order can consist of a number of order lines and delivery moments. Cells producing parts that are used for the same assembly are hence simultaneously related, as the assembled product will be delivered to one customer. If the parts that are produced in the two cells have to be delivered at different moments to the customer, although they belong to the same order, these cells are still simultaneously related according to the definition given. Simultaneously related cells have the possibility of sharing information, e.g. on the progress of the connected activities or on the liability of the joint customer. Suppose that several cells produce for the same assembly. A cell might benefit from obtaining information on the delivery dates that the other cells can guarantee. The planning within the cell could possibly be improved using this information of the simultaneously related cells. If a simultaneous cell has a machine breakdown that delays the production of parts for an assembly for which the current cell also has to produce, then it will not be necessary to give priority to a component for this product in the current cell. Sharing the available information on due dates makes it possible to update the planning of all simultaneous cells. Note that the assembly cell itself will not benefit from sharing this information with the delivering cells.

Simultaneous relations can also occur due to specifications in a process plan, concerning, for example, the specifications of the raw material that has to be used or the time frame in which both operations in the different cells have to be performed. If these cells can benefit from sharing information on the related activities they perform, the cells are simultaneous related.

Latent relations between cells are defined in a more abstract sense. They exist if in the production system flexibility is available that can be used to create or change a sequential or simultaneous relation between the cells.

An important type of latent relation can be found in the presence of a *pool of shared resources*. These resources are not allocated to specific cells, but a cell can have the disposal of such a resource. The flow of the shared resources is often not planned, and the time at which the resources are really needed by the

cells is frequently not known to the system. This makes it possible that conflicts between cells arise if more cells want to have the disposal of one of these resources at the same time. Cells are latent related if this can occur, e.g., if a specific resource can be claimed by both cells for the production of the currently known orders. For the existence of a latent relation between two cells it is not necessary that the shared resource will be interchanged between these cells, as is required in case of a sequential resource relation between these cells. There might be a third cell that is sequentially related with both cells in delivering a specific resource.

The second type of latent relation is caused by the available flexibility between cells in the already determined specification and allocation of operations, resources, material and information. So this type can be encountered if it is possible to specify and prescribe an alternative process routing for an order by using another cell instead of the current one, in that way creating a latent relation between these cells. This can only occur if both cells are not completely disjoint, which happens quite often in small batch parts production due to the allocation of similar machines to the various cells.

In this section we presented a categorization of relations between cells, distinguishing between sequential, simultaneous and latent relations. These categories can be used in determining the external primary coordination requirements in a cellular manufacturing system. In the second part of this paper we illustrate its usage in five short case studies.

6. Relations between cells in practice

Three types of relations between cells are distinguished in this paper. In this section we show the usage of this distinction in determining primary coordination requirements between cells and we describe the corresponding coordination mechanisms applied by the firms. The focus is on relations with cells in the parts production processing stage. We do not aim to present all relations that existed between these cells in the cases we studied. A selection of these relations will show the usefulness of the classification we made.

6.1. *Sequential relations*

We deal with five types of sequential relations and show the differences in coping with these relations between the cases. The first sequential relation that we studied is between a prefabrication cell and a parts-producing cell. In all cases raw material was centrally prefabricated in a cell that also performed the warehousing function and often even tool management (e.g., storage, preparation, presetting). However, the mechanism that was used to control the delivery to the parts-producing cell differed per firm, as can be seen in next table.

Sequential relation with prefabrication cell					
Case	I	II	III	IV	V
Push/Pull	push	pull	push	push	pull
max. lead time	1 day	4 days	no max.	no max.	2 days

Two cases used a pull system to control this delivery, which means that orders were released to the parts-producing cell and that prefabrication could only start if the parts-producing cell had handled the material request to prefabrication. The other three cases used a push mechanism, so orders were first released to the prefabrication cell. This cell prepared the required material and reserved it for or delivered it directly to the parts-producing cell. The available time for this operation was explicitly restricted in three cases. The decision to use a pull or push mechanism has consequences for both the total amount of work in process and the efficiency that can be achieved in the prefabrication cell.

The second sequential relation concerns a relation between a parts-producing cell and a cell at the same or a former processing stage. If this relation is present, the way it is coped with interests us. The next table presents the relations we found in the cases studied and the policy with respect to the use of this relation.

Sequential relation with a cell at the same or a former processing stage					
Case	I	II	III	IV	V
Former stage	not present	not present	present	not present	not present
Same stage	present	present	present	present	present
Usage frequency	incidentally	incidentally	structurally	structurally	structurally

As can be seen in this table, all firms encountered this type of relation between cells, but the way they coped with it is different. Case I and II only used this relation incidentally, e.g., in case of a machine break down, by switching the work temporary to another cell. These firms did not structurally use this flexibility, as they preferred to subcontract the work to avoid disturbing the processing in the other cells. Generally, the load of the other cells prohibited the interchange of work; interchange of work would delay orders that had already been released to these cells.

The other three cases encountered these relations structurally. Case IV and V designed their cellular system such that no more than 10%-20% of the orders have to be processed sequentially in more cells at the same stage. Both firms considered this percentage to be unavoidable, as duplication of the required resources was economically not justifiable. The coordination of this relation was a problem in case IV, where the cell who performs the first operations is held responsible for the final delivery performance of the order. If this cell transfers the work to the next cell, the latter is often not willing to give priority to orders for whose delivery performance they are not responsible. A reason can be found in the resulting machine load not being taken into account in the planning of the second cell, i.e. in the capacity profiles made for this cell.

Case III had both structural relations with cells at the same and at a former processing stage. These relations were for a large part caused by the processing sequence of one module. After preprocessing has taken place, this module is

processed in the welding cluster and afterwards the mechanical cluster is involved before it is put in stock. However, the flow between the welding cluster and the preprocessing cell is bidirectional. When the last welding operation is completed, the module is first returned to the preprocessing cell which also performs some finishing operations. The required inspection of the finishing work is again done within the welding cell. The firm preferred this relation in the main flow because (1) the utilization of the finishing machines was too low to create a separate cell, (2) the finishing work was considered too simple for performing it in the welding cell, and (3) the skill level of the finishing operators was comparable with the prefabrication operators.

The third sequential relation describes the existence of relations due to operations that are performed by an internal or external subcontractor (here regarded as a special kind of cell). An example of an internal subcontractor is a quick service or a separate machine within the shop used by more cells. External subcontracting means here the subcontracting of part of the work that had already been allocated to a cell. It can be used for capacity reasons or because the required operations cannot be performed within the firm, which is often the case with surface or other finishing operations. It is important to describe the flow of material after the subcontracted operation has finished. Is it to be returned to the parts-producing cell to continue processing or is it to be delivered to the warehouse? This affects the way to cope with these primary coordination requirements, both externally and internally.

In the next table an overview of this third type of sequential relation in the five cases is presented. The first row describes the usage that is made of external subcontracting due to capacity reasons. In all cases but one the surfacing operations were externally subcontracted. The second row describes the return flow of material after the work had been subcontracted for a surfacing operation. If (part of) the work is returned to the parts-producing cell, it is denoted by *cell*, otherwise by *warehouse*. The last row describes the presence of internal subcontracting to a separate department.

Sequential relation with external subcontractor or internal separate department					
Case	I	II	III	IV	V
External Capacity	incidental	structural	incidental	incidental	incidental
Surfacing: Return to	cell	warehouse	warehouse	NA	warehouse
Internal	NA	NA	heating	NA	quick services

Subcontracting work that had already been allocated to a cell due to capacity reasons was in most cases restricted. Only one case used this form of flexibility intensively. The cell foreman was allowed to decide on his own on subcontracting work. Subcontracting due to these capacity reasons was here often preferred to changing the planning of the cells by reallocating the work, and adequate procedures for subcontracting had been developed. For example, the cell stays responsible for delivering the correct information, material, and tools (if necessary), and for the lead time performance on the subcontracted order. Much of the production flexibility in the firm was found in this subcontracting system with near door subcontractors. This resulted in a very high utilization of the cells, as frequent disturbances caused by the transfer of work load between cells were avoided.

If the return flow of subcontracted material is directly to a cell for further processing, the cell ought to be informed about the arrival of the work. Providence of information with respect to the expected return moment of the subcontracted work would enable the cell to make a realistic planning of the resulting work load. Case I did not use planning as a coordination mechanism for this relation with the external subcontractor. Instead it used a large amount of slack time. In most of the cases, the work was returned to the warehouse and the planning department allocated the work to a cell if further processing was necessary.

Two of the cases used sequential relations with separate internal departments. The handling of these flows was done differently. In case III the internal

transport system was used, while in case V the cell who had to continue processing brought the material to the departments.

The fourth sequential relation is between a parts-producing cell and a finishing cell. This relation is especially important if more parts-producing cells have this relation with one finishing cell. A finishing cell can often process only one arrival at a time and is usually the last cell involved in producing the order, so the lead time performance of this cell is very important. We describe the type of coordination for this cell as well as the instruments used to avoid long delays in the delivery of the product. In the following table we first describe the number of parts-producing cells that deliver the finishing cell. Second, we mention the priority planning procedure applied for this finishing cell. Finally, the instruments used to manage the capacity of this cell are enumerated.

Sequential relation with finishing cell					
Case	I	II	III	IV	V
Delivering cells	all	two	one	all	all
Priority planning	FIFO	FIFO+informal	NA	FIFO/EDD	NA
Capacity management instruments	overcapacity, overtime, temporary workers	overcapacity, subcontracting	overcapacity, flexible operators	planning to regulate flows	overtime, temporary workers, subcontracting

Three of the five cases made use of overcapacity, e.g., allowed underutilisation of the machine capacity in the finishing cell. Although the capital invested in this cell was generally high, these firms gave priority to a complexity reduction in the management of material flow and capacity. Through the use of overcapacity, a strongly fluctuating incoming flow of material accompanied by required throughput times that ranged from 1 to 4 days could be handled. The other two cases used another strategy. In case V the finishing

department had less overcapacity, while all parts-producing cells delivered to this cell. As an instrument for capacity management, this firm hired temporary employees for preparatory activities in the finishing department. Case IV used planning as an instrument for capacity management. The expected load of the finishing cell in the next week was presented to the parts-producing cells and the incoming flows of material were regulated based on this profile. Note that in this way not only the sequential relations between the parts-producing cells and the finishing cells were used, but that also the relations between the parts-producing cells were recognized in planning the system, as will be further discussed in the section on simultaneous relations.

The last sequential relation describes the relation of a parts-producing cell and a cell that performs assembly operations. These operations can partly be decoupled from the operations performed within the parts-producing cells by specifying and communicating a planned start date for the assembly operations and by using a buffer policy, e.g., using safety stock or safety lead time. However, coordination can also be performed by planning the flows to the assembly cell in detail or by using the available flexibility in the planning within the assembly cell, e.g., by changing the sequence in assembling the various modules. In that case, the size of the buffer can be much smaller. In the next table we describe the type of planning of these sequential relations with the assembly cell and the buffer policy used.

Sequential relation with assembly cell					
Case	I	II	III	IV	V
Planning	flow of parts planned in detail	flexible planning within assembly cell	planned start date of assembly	planned start date of assembly	not planned
Buffer policy	safety lead time	safety lead time	safety stock	safety stock	no buffer

In case I the planning of the assembly cell is used to plan the flows from the

parts-producing cells in detail. Case II planned the start date for the assembly of a complete installation. This installation consisted of various modules that had to be assembled. The required parts for all modules had to be present in the warehouse three days before the planned start date of the assembly of the complete installation. So the coordination of the flows from the parts-producing cells was based on this overall start date and not on a detailed planning of the assembly cell that specified the planned start dates of the individual modules. This gave case II the opportunity to use the available flexibility in the planning of the assembly cells if problems with respect to the incoming flows occurred, but it resulted also in a higher total amount of stock. Case III and IV used safety stock as a buffering policy for a large percentage of the parts that were required in the assembly. Case V did not recognize that for the welding of some complex products in the preassembly cell the coordination of the required parts flows was necessary. The due date for the required product was specified in the planning, but the start date for welding the product had to be determined by the foreman of the welding cell. The stock of required parts that was kept in this cell was not controlled. This resulted in an unexpected arrival of orders for these parts with very short lead times in the parts-producing cells, which caused disturbances in their own planning and a very low lead time performance on the assembly products. This illustrates that it is important to recognize the existence of this type of sequential relation and to select an adequate set of coordination instruments.

This description of five types of sequential relations in cellular manufacturing and the discussion on the resulting coordination requirements and the various coordination mechanisms applied illustrates the complexity of problems on the external primary coordination level.

6.2. *Simultaneous relation*

In this section we give some examples of simultaneous relations between parts-producing cells that we encountered in the five cases studied.

In case I the products were painted in one of the three available colors in the finishing department. Two of these colors were used regularly, but usage of the

third was not often specified in a process plan. To use the required material and resources more efficient, the simultaneous relation between the cells producing parts that require this color ought to be recognized by this firm. The planning of these cells could then be tuned with respect to this relation to determine an acceptable start date for the required painting.

The sequential relations between parts-producing cells and the finishing cells in case IV were coordinated with the use of planning as a coordination mechanism. In this way also the simultaneous relation between the parts-producing cells was recognized. These cells were informed on expected peaks in the load of the finishing cells for the next week and were able to regulate their flows to this cell by mutual arrangement.

Case III did not recognize the simultaneous relations in the production of module Y. The sequence of processing this module consisted of five steps, but more than five cells were involved in the production of the module, as some of them produced in parallel. If one cell could not finish its production on time, the next cells in the processing sequence were notified. However, cells in the same processing step that produced simultaneously for the same module were not notified of the expected delay. So they still tried to produce their parts on time, possibly delaying other parts or using overtime.

Case II, IV and V encountered these simultaneous relations between cells that produce for the same assembly. As could be seen in the former section on coordinating the sequential relation between an assembly cell and a parts-producing cell, the material flows from the latter type of cell were not planned in detail. The mutual relation between these parts-producing cells can be regarded as a simultaneous relation. In the planning of these cells information on the planning of the other cells could be used, but these cases did not use this information explicitly. However, they recognized that usage of this relation could improve the overall performance of their cellular systems.

6.3. *Latent relations*

The last type of relation that we distinguish is a latent relation. Latent relations between cells for which the direction of the flow not yet had been determined

were found in all cases, due to the existence of pools of shared resources. We could often easily detect these pools by looking for a central storage location of the tools and fixtures. Central storage almost always implied that shared usage of these resources was allowed, even if the particular resource was duplicated. Other examples of latent relations caused by sharing of resources were found in case II and III. In case II the tools shared by the assembly cells could restrict the planning within these cells. In case III the transportation equipment for handling material within the cells was shared, potentially causing delays in the progression of the production. None of the five cases did register which cell had the disposal of which tools. In case V 5% of the orders are delayed due to the required tools being not available at request. In case I, II and III tools have mainly been duplicated. Case IV and V also had duplicated tools, but this solution was considered here too expensive. They had more problems to justify this investment economically, but still preferred this solution to buy themselves out of trouble.

The next latent relation we consider here is caused by the possibility of allocating an order to more cells. If both cells are able to perform the required operations, we can choose to what cell the work is released. In case I, II and III this relation existed for only a small percentage of the orders. Case I and II did not use this flexibility, case III incidentally. Case IV and V encountered this relation for a large percentage of the orders. Case IV incidentally used this flexibility, while case V used this flexibility intensively in their planning system by letting the cell foremen choose among the available orders.

Latent relations due to the existence of alternatives could be seen in the reallocation of operators to another cell. The cases coped differently with the resulting coordination requirements. Case I and III had explicitly defined human resource pools. These pools were restricted to a cluster of cells and the people in these pools could change to another cell in case of illness of a cell member or rush work. Human resource pools are generally used for a short period and can be asked for at a short term. Another coordination mechanism that was used is temporary reallocation of operators, e.g., for a period of one week. This was considered in case I and II when they discussed the production plan for the next

week. Case IV and V only incidentally used this kind of flexibility.

Another latent relation can be encountered due to alternatives in the process plans. In case I this relation is recognized in the loading of a temporary bottleneck in a particular parts-producing cell. If the cell workers concluded that this machine became overloaded they could interchange work to another cell. In this cell the NC programs were rewritten, which could be provided within 15 minutes. In case IV interchange of work was also possible, but here rewriting the programs was done within the engineering department, causing a two-days delay and flows of information between the cells and this department. Case V was not even able to rewrite the programs within a reasonable time, so they were not able to use this latent relation between the cells.

In this section we demonstrated the existence of three types of relations between cells for the five cases that we studied. The differences between the cases were illustrated by elaborating on the way they coped with the coordination requirements that resulted from these relations.

7. Conclusion

In this paper we have analysed the coordination requirements between cells due to the primary transformation process of the production system. The production situation of small batch parts producing firms that use cellular manufacturing has functioned as a frame of reference.

The literature on cellular manufacturing gives the impression that the coordination issue within cellular manufacturing is rather easily tractable because the flow of material between cells had been minimized and the problem of scheduling the flows within the cells had been solved by decentralizing the planning tasks to the cells. In this paper we have concluded that this is a far too simple view of the coordination issue within cellular manufacturing. The flow of material between cells is not the only type of flow that has to be considered, as the flow of resources and information also has to be taken in consideration in small batch parts production. Furthermore, the flow of material between cells is often more complex than described within this literature due to factors such as subcontracting work and assembly operations. Finally, the material flow

generates different coordination requirements in different situations.

We have elaborated on these coordination requirements between cells and have described first two levels of coordination within cellular manufacturing (internal and external), and second the object of these coordination requirements (primary or secondary). We have focused on the external primary coordination requirements, i.e. the coordination between cells needed to proceed with the primary process, and have distinguished three types of relations between cells: sequential, simultaneous and latent relations. Sequential relations describe the existence of flows between cells, simultaneous relations the existence of parallel connected activities, and latent relations the existence of flexibility in the process plans or in the production plan with respect to the allocation of operations, resources, material or information to the cells. Introduction of these three types of relations between cells results in a more comprehensive description of external primary coordination requirements and in this way a better understanding of the complexity of the coordination issue within cellular manufacturing can be obtained.

This is illustrated with five short case studies, for which we have analysed the three types of relations. We have presented a selection of the observed relations and have used them to identify specific coordination requirements between the cells and to describe the differences between the cases in coping with these requirements. The main conclusion we have drawn from this analysis is that both the recognition of and the way to cope with external primary coordination requirements are very important. The disclosure of specific relations between cells has made it in some cases possible to identify deficiencies in the application of adequate coordination mechanisms. Finally, comparing the coordination mechanisms used by the cases for similar coordination requirements has allowed us to present alternative coordination mechanisms for these situations.

The coordination issue in firms that use cellular manufacturing in their production of parts is highly complex due to the various flows that have to be coordinated and the flexibility that has to be present in the system. We have shown that the use of the three types of relations between cells helps to identify

external primary coordination requirements.

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