A hierarchical approach to structuring the production control in multi-product multi-phase production systems

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MODELLING PRODUCTION MANAGEMENT SYSTEMS
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A HIERARCHICAL APPROACH TO STRUCTURING THE PRODUCTION CONTROL IN MULTI-PRODUCT MULTI-PHASE PRODUCTION SYSTEMS

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This paper presents a qualitative methodology for designing hierarchically structured production control systems for complex production situations. The methodology is based on the assumption that complexity should be reduced by defining self-contained subsystems with clear and well-defined operational characteristics. Furthermore the interactions between the subsystems should be simple and restricted. We introduce the Production Unit as a basic control entity, and the problem of coordinating the production units in a system is analyzed on the basis of the operational characteristics of a unit. Finally we discuss the concepts of Master Planning and Materials Coordination as basic coordination mechanism, and analyze the process controlled by these mechanisms. We show how production unit control, materials coordination and master planning interact to realize maximum flexibility to demand variation with minimum slack.

INTRODUCTION

Production control refers to the coordination of production and distribution activities in a manufacturing system to achieve a specific delivery reliability at minimum costs. In many customer oriented production situations the manufacturing activities have developed in such a way that manufacturing is specialized according to producttype and/or to manufacturing technology. The result is a production structure with a number of production units, where each unit takes care of a separate part of the production, and where the goodsflow in and between these production units can be quite complex. In such a production system, each of the production units will have its own short-term and long-term goals, whereas each product-type delivered to the market may require materials and capacity from a number of different production units.

In order to realize the required delivery performance in the market, coordination of the activities of the production units is therefore necessary. These coordination activities, however, should not conflict with reaching the production economics objectives for each of the production units. On the one hand, realizing production economics objectives is in the interest of the system as a whole. On the other hand however, the production units should show high flexibility with respect to reacting to changing market conditions, demand forecasts, and actual demand. Lack of flexibility may lead to high and unbalanced stocks, poor delivery performance, and possibly loss of market position. This conflict between short-term interests of production units and goods flow control is well-known in literature.

In the past decade a number of studies have been published on the design of hierarchical production control systems. Many of these studies reported on the principles underlying particular design projects in practice (e.g. Bitran and Hax [1977],Hax and Meal [1975]).Other research used mathematical analysis to investigate specific types of aggregation and decomposition (e.g. Axsäter [1979], Zipkin [1982], Wijngaard [1982])or used systematic computer simulation for this purpose (e.g. Shwimer [1972], Jönsson [1983]). In this paper we deal with a different aspect of the problem. We study the subject from the point of view that the control subproblems at any level should be defined such that the controllability of the problem as well as the actual control performance can be measured and therefore can be monitored. This requirement follows from the fact that the control procedures are implicitly or explicitely based on formal models of the processes to be controlled, and that it therefore must be possible to check the validity of these formal models. We have used this approach in a previous research project on production control in a production unit (see Bertrand and Wortmann [1981]) and are now applying it to a more complex production problem. This paper reports on a part of this research.

During the last decade, markets have gradually shifted from seller's markets to buyers' markets. This change has urged the production systems to increase their delivery performance and their flexibility. In many places new types of control systems have been developed to support these efforts. One of the best known techniques in this respect is Materials Requirements Planning (MRP-I), which in essence aims at decreasing the reaction time of the goods flow, by immediate and direct feedforward of new demand information to the production units. In fact, the approach narrows down to reduction of uncertainty in the production system.

Reduction of uncertainty can indeed be an important aspect of improving the production flexibility. However the classical MRP-I approach neglects the fact that the ability of the production units to use this information (that is, to realize flexibility) can be quite restricted. The next step therefore has been the development of the conceptual framework for production control known as Manufacturing Resources Planning (MRP-II), which deals with the problems of shortterm and longterm inflexibilities in the production units. (see e.g. New [1977], Plossl and Welch [1979]). Specifically, the concept of a Master Production Schedule (MPS) has been introduced as a device to reconcile the conflicts between markets needs and production possibilities (see e.g. Berry, Vollman and Whybark [1979]).

The MRP-II concepts were a substantial step forward in the design of goods flow control systems. However, a real quantitative basis for the operational design of such systems is still lacking, as can be concluded from the many difficulties encountered when MRP-II is being used as a basis for design in practice. This paper aims at filling a part of this practicality gap. It introduces some basic concepts for designing production control systems which achieve high flexibility while still enabling the production units to realize their production economics. For this purpose, we first introduce definitions of basic concepts for describing a production system, such as items, materials, capacity and operations. Then we introduce the concept of Production Unit, which is used as a homogeneous logistic entity. The coordination of the production units is referred to as goods flow control. Next we define the Master Planning problem and introduce the concept of the Master Plan which is defined as the outcome of the process of reconciling the production possibilities and market needs. We will show how the production control problem can be split up into the following hierarchically ordered subproblems

- reconciling production limitations and market needs by periodically generating a Master Plan, based on the actual state of the production system and its possible future transformations. In this process production units are treated as black boxes
- generating during a period, production inputs to the production units based on the Master Plan which aims at coordination of the activities of the production units
- controlling the actual inputs to each production unit based on the internal state of the production unit, the coordination inputs and the requirements to realize the production economics.

In this paper we will concentrate on the first subproblem. However, as the three types of subproblems are highly interdependent, it will be necessary to also pay some attention to the other two subproblems.

In principle we can distinguish three basic sources of inflexibility that is inherent in a production system. These are:

- inflexibility due to the manufacturing technology and organization of the system (machines, operator skills, layout, buildings, etc.)
- inflexibility due to operational relationships between production variables such as capacity utilizations, work orders flow times, work order release frequency, set-up time, etc.
- inflexibility due to the chosen production control system (decision frequencies

detail and scope of available information, time it takes to make a decision, quality of the decisions, etc.).

In this paper we concentrate mainly on the effects of the second kind of inflexibility, on the possible structures of the production control system. Therefore, we first shortly discuss the nature of the relationship between operational relationship and control structure.

OPERATIONAL RELATIONSHIPS AND CONTROL STRUCTURE

Generally the design of a production control system for a specific situation starts from assumptions regarding the operational relationships between the production variables. The inflexibility or constraints inherent in this model determine the maximum delivery responsiveness that can be achieved by any production control system. However, achieving this maximum delivery flexibility is generally unrealizable because information processing and decision making takes time itself. Moreover, the costs of the production control system should be offset by its benefits. Therefore the best production control system from an overall point of view will generally not be the best possible system from a pure logistical point of view. Often the marginal costs of using more complex control models are very high, whereas their marginal benefits can be quite low. Therefore, in the design phase various control structures and models at different levels of complexity and quality should considered and evaluated with respect to their logistical and economical suitability. For instance, for a multi-phase production system we may choose between having a set of independent control systems per phase, or having a base-stock system which guarantees integral control over the phases, or having an MRP-system which also takes into account available knowledge of future demand.

The control structure chosen for a specific situation generally will induce additional constraints and inflexibilities regarding the responsiveness to changes in the environment and in the company policy. Note that this type of inflexibility is built-in in the design phase,and should be a explicitely decided upon.

The basis for the selection process regarding alternative control structures is the model of the operational relationship or constraints between the production variables. In building this model we assume the manufacturing technology and the organization of the production system to be given. Thus the inflexibility inherent in technology and organization is incorporated in this model. However, in many situations in practice, changes in technology and organization are possible certainly on the medium and long term. Therefore, after having modelled the operational relationships as they are in a given situation, and after having considered the inflexibilities and constraints implied by this model, we also should investigate the possibilities of reducing the inflexibility by changing the technology and/or the organization. A well-known example in this respect is the reduction of set-up times by changing the design of machines and installations, thereby eliminating the change-over and batch-size problem. Such technological changes of the production control problem should always be evaluated in terms of their economical value and organizational acceptability. In order to evaluate these alternative solutions, we need a theory of how to design an adequate control system for a given problem, defined by some set of operational relationships.

We see that the model of the operational relationships should always be at the heart of the design process. It is the basis for developing and evaluating possible control structures and the basis for comparing the consequences of possible technological and organizational changes. An extensive discussion of important types of operational relationships or constraints will be given in a later section.

SYSTEMS BOUNDARY

We assume that for any production control problem in practice a systems boundary can be determined. The systems boundary tells us what "part of the production world" is considered and what part is out of our scope. The systems boundary should be established operationally by specyfying the inflows and outflows from the environment into the systems considered and vice-versa. Inflows from the environment to the system are incoming materials, incoming customer orders, and actual changes in the production capacity. The outflows to the environment are the materials procurement orders, the shipments of finished productions to satisfy customer orders, and instructions to change the production capacity of the system.This systems boundary concept is illustrated in Fig. 1.

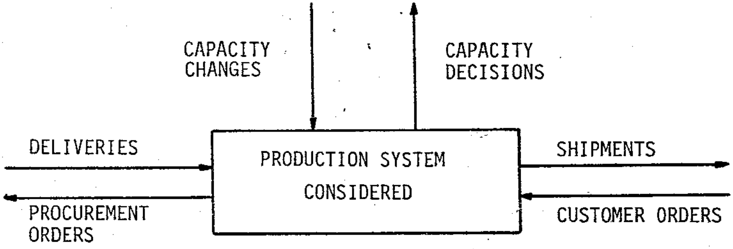

Fig. 1. The boundaries of the production system.

The next step in defining the production control problem is to specify the external and internal relationships of the system.External relationships pertain to the behaviour of the environment of the system; that is,to how inputs to the system are related to the output of the system (how are incoming materials related to the procurement orders placed etc.). Internal relationships refer to the process which transforms the incoming materials, given the available capacity, into the outgoing finished products. For this purpose we assume the manufacturing processes to be given. Thus for each finished product (end item) the following are known

. the end product structure, which is the way in which the product is composed of materials, parts or components, and subassemblies.
. the capacity types needed,
. the manufacturing steps which are needed for each of the components, subassemblies and final assemblies in the product,
. the amount of capacity required for each manufacturing step.

Given this general specification of the system we can roughly define the production control problem as follows:
Given certain consistent objectives regarding customer delivery performance and manufacturing costs, how should we:

1) accept customer orders
2) place procurement orders
3) vary the capacity
4) allocate available capacity to manufacturing steps.

Depending on the system boundary chosen, the complexity of problem can vary over a wide range. For instance the boundary can be chosen such that the internal structure only refers to a dedicated assembly line for one finished product, or it can be chosen such that it encompasses a multitude of finished products, with specialized production departments for the manufacturing of components, subassemblies and assemblies. In this paper we want to contribute to production control for systems of the second kind. We restrict our research to production systems with many complex end-items, where interactions and relationships between products and their timing stem from the following factors:

- the products use shared capacity resources, which are restrictedly available because of production economics. As a result the products may compete for capacity, and waiting time may occur which may be part of the manufacturing lead time of the produc
- the products use shared types of materials and subassemblies

- information on marked demand is only limitedly available, at least in time. As time proceeds more and better information may come available regarding the customer demand in a specific period. For different products these demand-information profiles may be different, and also, per product the profile may change over time.
- because of the need to achieve certain ordering and/or production economics, materials procurement orders and production work orders are released with batch sizes which may be larger than the immediate required amount.
- short term capacity variations are possible at specific costs, to a limited extent and with a certain leadtime. Long term capacity is mainly driven by technological developments, which are outside the scope of this paper.

BASIC CONCEPTS

Materials, resources

We assume that the manufacturing process for an end-item can be defined as a related set of transformations. Each transformation may require materials and/or resources. As materials we define other items which are absorbed in a finite discrete amount during the transformation step. As a resource we define objects which are not used-up during the transformation step, but which are only used during the transformation step. (machines, space, etc.). This distinction is not absolute, because in the long run also resources are depleted during the manufacturing steps, due to wear, etc. However, within the time frame of the production control problem, the availability of resources is not seriously affected by its assignment of the manufacturing steps. On the other hand, materials are those items whose availability is affected by assignments to a manufacturing step (the items are depleted). As a consequence the replenishment of these items for future manufacturing steps is part of the production control problem. A resource therefore is an object which, after assignment to a manufacturing step, is used during some time and which after that step is available again in its original state for other manufacturing steps. A material is an object which, after assignment to a manufacturing step, is no longer available for other manufacturing steps.

Operations

A manufacturing process is a network of manufacturing steps. For the purpose of production control the manufacturing steps are aggregated into operations. The specification of operation should be related to the scope of the production control problem at hand. The operations generally do not follow straightforwardly from the description of the manufacturing steps, but must be based on the aspect of the system that is addressed by production control. Now as production control addresses the *timing* of the allocation of resources and materials, a natural criterium for the grouping manufacturing steps into operations is their relative independence in time. Thus if there is little freedom in relative timing of a group of manufacturing steps, it would be natural to consider this group as one operation, which requires the resources and material of all the manufacturing steps in the group. From the production control point of view, an operation is a black box with specific properties, and which is not subject to internal manipulation.

From this view on the definition of operations, it follows that an operation in itself is not given by nature, but in principle can be influenced at the stage where that production control problem is defined. We conclude that the grouping of manufacturing steps into operations is an explicit decision phase in the design of a production control system. Using more aggreage operations (involving more manufacturing steps) may decrease the complexity of the production control decision problem (less operations have to be considered) but may also reduce the controllability of the problem (more decision freedom is taken out of the production control and is "frozen" in the definition of the operations). It follows that depending on the control performance required we might even group manufacturing steps which are rather independent into one operation, just because this simplifies the control problem to be solved, if the implied loss of decision freedom would not seriously harm control performance.

Generally, an operation has the following attributes:

- the time required for the operation (the duration of the operation),
- the pattern of capacity requirements during the operation,
- the requirement state of the materials needed for the operation, at specific points in time during the execution of the operation,
- the state of the material after the completion of the operation.

In order to simplify the control problem to be solved, we require that an operation should be defined such that the time phasing of materials and resources required during the operation are only related to the progress of time after the starting of the operation. In other words, no interactions exist between (or is assumed to exist), between the time pattern of resource requirements and materials requirements. Thus we define an operation as a static entity.

PRODUCTION UNITS

The next basic concept that we want to introduce is the production unit. Ideally, a production unit (PU) is a combination of a set of capacity types, a set of operations and a set of materials with the following properties:

- for each set of operations to be performed, it is only required to use materials from the set of materials, and to use capacity from the set of capacity types
- each capacity type in the set of capacity types and each material item in the material item set is only used for performing operations belonging to the operations set.

Thus this basic concept implies that in a production organization there may be specific sets of capacity types and specific sets of material types which are dedicated to the production of specific sets of operations.

The introduction of production units in a production system in principle decreases the decision freedom in the system; at some early time specific capacity and specific materials are dedicated permanently to specific operations. However, the introduction of production units also reduces the complexity of the decision problems which often will improve the quality of the organization per production unit. It also may lead to improved models (both mental and formal) of the decision problems, and may improve the decisions taken. A production unit therefore should be introduced as a distinct entity in a production system if we expect that the effects on the performance of the resulting loss of decision freedom is offset by the improvements in internal and external decision making.

An ideal production unit is self-contained from a manufacturing point of view. Also from a production control point of view the production unit is self-contained, but it generally is constrained with respect to the amount and timing of its production. These constraints constitute the operational relationships of a production unit. The constraints are basically generated by its limited availability of capacity and by the operation processing times required for the manufacturing of the items. However, additional constraints can be generated by the way in which a production unit organizes its production process in order to realize specific objectives regarding product quality and production efficiency. For instance, if set-up times are an important part of the operation processing time, then the PU may want to work with specific batch sizes. Moreover, if for a specific machine set-up times are sequence dependent, the PU may want to maintain a certain working stock of work-in-process at that machine in order to be able to create an efficient production sequence.

The creation of a PU requires a relatively stable environment for that unit with respect to the availability of resources and the demand for product items produced by that unit. This stability is required because the PU will operate in relative independent way, and therefore it will need a number of environmental invariabilities to base its internal structure on. Thus the creation of a PU will only improve the performance of the system if we can provide the PU with a stable environment, so that it can generate an internal control structure that takes maximum advantage of that environmental stability. To the extent that this environmental stability is lacking, the PU will have to show flexibility and therefore it will invest in organizational procedures to generate this flexibility. Also the lack of stability will have an effect on the amount of communication required between the PU and the overall production control function in which the PU is embedded.

The advantage of defining and using production units in a production system stems from the reduction of complexity of the problem. First, for each PU,the problem exists of how to achieve the agreed performance,given that the environmental conditions are and will be according to the norms. Each PU can solve this problem separately. In the remainder we will refer to this problem as the PU-control problem. Second, there is the remaining problem of how to realize for each PU the agreed environmental conditions, and to realize at the same time the overall production control objectives. We will refer to this problem as the Goods Flow Control problem. From the perspective of Goods Flow Control, the PU's are black boxes, which have specific operational characteristics, and which only can be influenced under certain conditions via specific inputs. These conditions reflect the agreements regarding the environmental conditions. For instance, an agreement could be that Goods Flow Control can release work orders to a PU, on the condition that the work load of that PU never exceeds a specific limit. On that condition, the PU may promise average delivery times of started work orders according to specific pre-set norms. A very different agreement might be that Goods Flow Control could release any work order to the production unit, and that the PU promises to deliver the orders according to variable due dates, specified at the time of release, which takes into account the actual workload at that time. Many more examples can be given of possible sets of agreements regarding performance and environmental conditions.

It will be clear that generating stable environmental conditions for a PU will be quite easy if the environment of the production system itself is rather stable. In fact,the "difference" between the actual stability of the systems environment and the stability implied in the agreed environmental conditions of the PU's has to be accounted for by Goods Flow Control. For instance, if the agreed condition per PU imply more stability that the systems environment shows, then the Goods Flow Control system should be designed such that it can absorb the difference. Goods Flow Control then could hold and use buffer stocks of finished goods or components to allow for the PU to adapt to the changes in the environment in a smooth way. On the other hand, if the agreements with the PU imply much flexibility, then Goods Flow Control can just pass the variations in the system's environment to the PU's. It should be remembered however, that for a PU, a stable environment can be beneficial for realizing a high operational efficieny. Therefore for each PU it is important to know the effects of environmental stability in variables like capacity load, planning horizon etc. on the efficiency of the PU. Dependent on technology used and internal organization, these effects may be different for different production systems. As a rule general statements in this matter will not be possible.

In order to monitor the control behaviour of a PU, models should be developed of the process controlled by the PU, which process in part depends on the constraints and performance agreements. In a previous research (Bertrand and Wortmann [1981]) PU-monitoring schemes have been developed for a particular PU-control problem in practice. Therefore we will not discuss this issue at this place.

GOODS FLOW CONTROL

From the point of view of Goods Flow Control, the PU's are black boxes. This implies that, apart from the operational relationships between input and output, the internal state of the PU's is not relevant for Goods Flow Control. The inputs to a PU however, are in part controlled by the Goods Flow Control system. Also, part of the state and the output can be observed by the Goods Flow Control System. However, which inputs are controlled and which outputs are being observed is part of the agreements on environmental conditions and performance, and they cannot be discussed in general terms. The decomposition of the overall production control problem in PU-problems and the Goods Flow Control problem only makes sense if this largely reduces the complexity of the resulting problems. Thus the number and frequency of inputs to the PU's and the number and frequency of outputs from the PU's by the Goods Flow Control should be much smaller than the inputs and outputs for the original overall problem where each operation had to be controlled on the detailed level.

This reduction of complexity can be realized by specifying *aggregate* agreements on the batch sizes and through put time of work orders released to a PU, in relation to the capacity load and/or capacity variations of the PU. It is essential that these agreements or constraints are aggregate in nature. In that case, many different mixes of work order released to the PU will satisfy the constraints. Therefore, for any mix which satisfies the constraints, Goods Flow Control can assume that the performance of the PU will be according to the agreed performance. This type of decomposition allows the Goods Flow Control System to neglect the internal state of the PU regarding the progress of work orders and the availability of materials and capacity.

From the point of view of the Goods Flow Control the PU is a system capable of transforming,within specific constraints the state of goods. Each possible transformation that can be realized by a PU can be defined on the production network of operations. Ideally, a PU should be defined such that the sub-networks per PU can be considered from the Goods Flow control viewpoint, as a single production phase. Then,for Goods Flow Control,the production processes for end-item can be expressed in terms of this set of production phases, and a set of relationships between these phases. In fact these sets constitute an *aggregate production structure*, which allows the Goods Flow Control to use a rather aggregate production model showing much less detail. Goods Flow Control does not deal with operations, but with production phases.

Controlled stock items, production phases

The basic control variable which constitutes the interface between Production Unit Control and Goods Flow Control is the release of new work orders to the PU. The release of a work order implies that the PU should complete the work order (that is to realize the transformations involved) within a specific time frame and with the use of a specific amount of capacity. The freedom of Goods Flow Control to influence the release and progress of workorders is restricted by the operational constraints. Thus, Goods Flow control only has a limited influence on the amount and timing of the work orders, and generally, by the nature of the decomposition, these influences refer to the timing of work orders release and the required completion time of the work orders. Thus Goods Flow Control only affects the start and completion of the work orders. As a result Goods Flow Control controls the output of items (components, subassemblies, etc.) from the stock points and the input of items to the stock point. Thus Goods Flow Control controls the behaviour of the stock levels of the items at specific points in the operations network of the products. These specific points are the manufacturing states in-between the PU's. Therefore we refer to these manufacturing states as controlled-stock items of the production process. The operations network between the controlled stock points, which are covered by the work orders in the PU we refer to as the production phase of a production process. The Goods Flow Control problem therefore can be defined as:

the control of the levels of the controlled-stock items, by means of the release of work orders for production phases, within the constraints set by the PU agreements, in order to realize a specific delivery performance at minimum cost.

OPERATIONAL CONSTRAINTS

The operational constraints of a PU specify the conditions on which the PU will perform according to specific performance norms.
In this paper we distinguish four types of operational constraints:

1) constraints on the batch sizes of work orders to be released. This constraint affects the costs of handling a batch, and the costs of setting-up a batch for each of the operations in a work order.
2) constraints on the sequence or combination of release of work orders. This constraint reflects sequence dependent set-up times and shared constraints for combinations of product types.
3) constraints on the workload of the PU. Generally, the workload can be expressed

in the terms of the number of batches in the PU, or the remaining processing time for all operations not yet processed. Sometimes it may be necessary to specify such constraints per capacity type in the PU. This type of constraint reflects the fact that in order to realize a certain utilization level of the capacity, it is necessary to have a specific working stock in the PU. This working stock creates production lead times which exceed the sum of the processing times of the operations of a work order. As such, a work in-process stock decreased the flexibility of the PU because, on an average, the processing of the released work orders will take longer.

4) Constraints on the change of the capacity level of the PU. Changing the capacity of a PU may incur costs, or sometimes changes may even not be possible at all on the short term.

Lead time

The first two constraints are related to product items, whereas the last two constraints are related to capacity. The production control problem would of course be easier to solve if these constraints just did not exist. In that case, production of all production units would be almost immediate (apart from the processing times), and we would only have to translate the customer demand during a period into work orders for the production units(on the basis of a simple material requirements calculation routine,which relates the items manufactured in a PU to the final products).However, due to the inflexibilities induced by the constraints,the manufacturing of items at a low position in the product structure often has to start long before customer orders are placed. Therefore, for these items production has to be according to a forecast or a plan. Deviations between actual demand and plan has to be accounted for at the start of each new decision period.

Material coordination

A second important effect of the constraints, in particular of the batch sizes and the sequencing constraints,is that it complicates the calculation of required production of an item from the delivery plan for end-items. If batch sizes are larger than the period demand, the requirement calculations have to be modified such that the actual production in a period is either zero or equal to the batch size. As a result, the dynamic behaviour of the stocks will now also be much more irregular. However, this is not the most complicating factor. These irregularities create interactions between the requirements of the items, which do not follow straightforwardly from the MRP structure. The release of a work order for a batch of an item is only possible if the material required for that item is available. These materials however are only available if earlier sufficient workorders have been released. Thus work orders released for different items should be synchronized to account for this effect.
The two factors discussed above, production lead time and batch size, are well-known and are accounted for in any modern MRP-I calculation routine. The problem however is that these MRP calcualtions assume that the shipment plan for end-items and the lead times are deterministic in nature. We will return to this point later on.

Production feedback

The third important effect of the constraints is related to the lead times. The lead times are mainly composed of the production throughput times of the work orders. The production throughput time is related to the number of work orders in the PU and the average production time required for a work order. Because a PU requires a specific number of work orders to be in the system, work order release should be controlled according to this norm. This means that the periodic differences between planned production and actual production of a PU should be fed back to the work order release. This creates a serious balancing problem, which has been recognized in the MRP II concepts (input-output control) but which has not yet been solved in a satisfactory way. For instance, suppose that production in a production unit has been less than planned. Clearly the next period we will have to release less work orders to compensate for this deviation, because otherwise, the throughput times of all work orders in the PU would increase, and as a result unpredictable materials shortages might arise in the future for work orders of other items. Releasing less work orders may also lead to shortages because of the work orders which are not (or later) released. However, now we can choose which work orders should be delayed for release, and we can try to solve the problem incurred. So in fact, the concept of workload control for a PU induces a serious inflexibility unless the production capacity of each PU can be varied to some extent.

Production Level coordination

The last important effect of the operational contraints is related to restrictions on the capacity variations per PU. These restrictions have consequences on two control levels. First, it restricts the extent to which the PU can correct the unpredicted production variations and demand variations . Each correction may take some time, or may be realized in a number of successive steps. As a result, a production deviation per PU at any time will exist.

Secondly, restrictions on capacity variations per PU restrict the extent to which we can react to predicted variations in production and demand (This factor is in particular related to aggregate production planning). Moreover, if the restrictions on capacity variations are different for different PU's, the problem is complicated further. We then have to account for two types of interrelationships between the capacity variation decisions for the various production units. First we have to take into account the fact that a PU cannot increase its production level unless there is sufficient material to release the required volume of work orders. Thus the production level of the PU's which manufacture the required materials should have been increased accordingly during the previous periods. For these latter PU's it is allowed to have a slower increase rate of the production volume, on the condition that the increase starts early enough. This will result in a build-up and build-down of a materials stock during a number of successive periods. We refer to this as production level coordination.

The second interaction between production level variations of PU's refers to the specific materials that are used to realize the production level variation in each PU. Even if the production levels are well coordinated, it is not guaranteed that the work orders released in one production unit create the specific materials needed for realizing the required production level in the other production units. Thus even if we would have solved the production level coordination problem, we still have the materials coordination problem. In principle these two problems, material coordination and production level coordination, cannot generally be solved independently.

An obvious way to avoid these coordination problems is to have a sufficient level of material stock in the stock points. This would allow the PU's to vary their production level independently. However, this will require such large average stock levels that all foreseeable differences in production level variation between the production units can be absorbed. As the purpose of this paper is to investigate production control structures which create a maximum flexibility with a minimum of slack, we will not consider this case and concentrate on the coordination problem.

THE PRODUCTION CONTROL STRUCTURE

Considering the huge complexity of the Goods Flow Control problem which follows from the previous analysis, it will be clear that finding a general optimal solution to this problem is very unlikely, even for a production system of moderate complexity and for a static situation. We propose to decompose the Goods Flow Control problem into a Master Planning problem and a Materials Coordination Problem. Master Planning controls the Capacity Use of the PU's and the Master Production Schedule for end-items. Decisions are taken periodically and pertain to the planning numbers to be used during the next period. Materials Coordination generates priorities for work orders to be released to the PU's, based on the actual state of materials availability and the current MPS.

The actual release of work orders to each PU is controlled on the basis of norms from all the three hierarchically ordered control levels: the Production Unit Control, the Material Coordination and the Master Planning. In fact the work order release decision is the place where the integration of these three decisions is realized. Figure 2 shows how the separate decisions from the three decision areas lead to the actual work order released. From this figure it follows that in this production control structure,the work order release decision is the pivot of all control decisions. Via the work order releases the decision from all the three levels are simultaneously implemented.

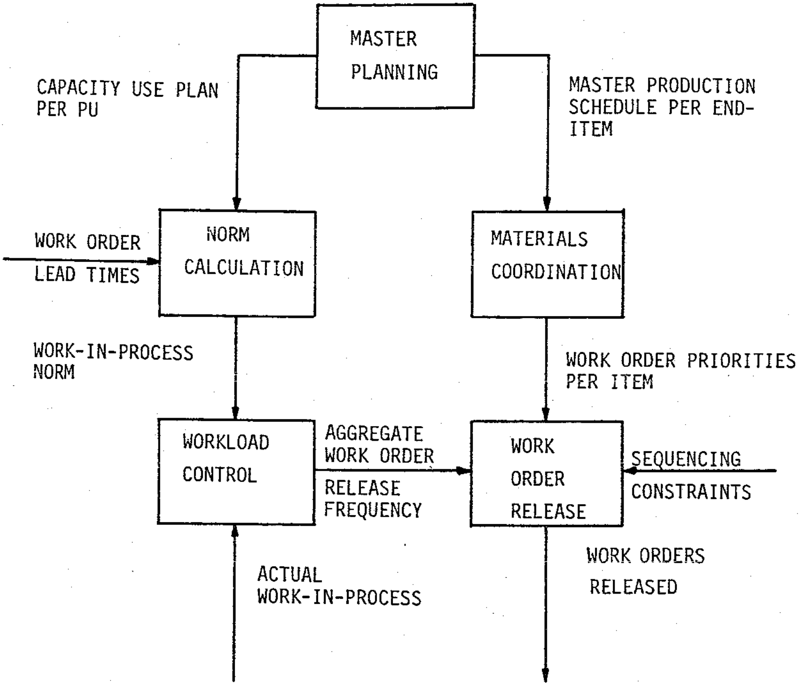

Fig. 2. The relationships between the various decision functions.

The nature of the master planning problem

In our control structure we use a Master Production Schedule on end-item level and a Capacity Use Plan for the production units as vehicle for coordinating the capacity variations and the workorder release per PU. The MPS and the CUP together constitute the Master Plan. The detailed decisions that follow from this process will transform the state of the system at the start of the period to a new, different state. This new state is in turn the starting point for a new round with possibly a new, different Master Plan as a coordination vehicle. The new Master Plan may deviate from the old one for two reasons. First,the actual new state of the system may differ from the state aimed at,due to unpredicted production variations, throughput time variations, unpredicted demand variations. A new actual state may require that the Master Plan is adapted in order to make it realistic.

Secondly, new market information may become available which leads to new required deliveries, which in part is within the range of possible deliveries, based on the actual state of the process.

It should be noted that the second reason is essentially different from the first one. The first reason is the result of the inflexibility in the system and the occurrence of unforeseen changes. The second reason is the result of the existance of flexibility in the system and the occurrence of new information (changes in demand forecast). Generally the inflexibility will affect the first periods in the Master Plan, whereas the second reason will have a larger impact on the more future periods in the Master Plan. Generally in the MRP II concept it is required that the MPS is realistic. This means that the capacity and materials consequences of the MPS are not in conflict with what is or can be made available. However, this requirement does not take into account the inherent flexibility of the state of the goods flow system at a certain moment. Therefore, we think it would be better to consider the MPS in principle as a coordination device. This implies that the MPS is a means to guide the transfer from one state of the goods flow to another. For this purpose the requirement that the MPS be realistic means that work order releases that the production units derive from the MPS can be realized. Also for monitoring purposes it must be possible to predict with some accuracy the new state of the goods flow that will result from these decisions.

In fact the only reason why we need a Master Plan is that we have to coordinate the actions of the production units. Thus because of the long lead times of some items, we need a plan with a similarly long horizon. However, we should keep in mind that this plan is really artificial and for the periods concerned many changes will be still possible (realizable). To capture the flexibility inherent in the state of the goodsflow we could in fact describe all the delivery trajectories which are realizable, given the current state of the production process. Such a set of realizable trajectories would show to the sales department the set of delivery options available, and as such this would be very elegant control device. However, we should keep in mind that such a set could only be realistically described in stochastic terms, as the real future deliveries not only depend on the current state and the future production control decisions, but also on a number of uncontrolled stochastic variabels. Therefore, this is not a realistic option.

The discussion above implies that each new period the sales department should specify a new proposed MPS,being a variation of the MPS which reflects best the new marketing information. This new proposed MPS then is modified to make it realistic on the one hand, and fitting to the new proposed plan, on the other hand. It will be clear that resolving the conflicts that will emerge from confronting the new plan with the current state may require priority setting between various end-items. This choise can best be made by the sales department which has information on the relative desirability of the end-items. In this way the sales department gets "the best" out of the production system without interfering with the production economics objectives of the production units; the available flexibility in the system is mobilized as much as possible.

THE AGGREGATE COORDINATION FUNCTION

Now we are in the position to describe the nature of the Master Planning decision function. The decision procedure we propose is based on the concepts of capacity echelon-stock and item echelon-stock. A echelon stock of a specific item in a production system is the total amount of this item in the system, be it as work-in-pocess, as stock, or as part of the work-in-process and stocks of higher level items of which this item is a part or a subassembly. Similarly we can define the concept of capacity echelon stock of a specific capacity type. The capacity echelon stock of a specific capacity type is the sum of all the capacity of this type which has been used for the manufacturing of echelon stocks of all items in the system.

For each controlled stock item and for each capacity type, a required echelon stock can be determined from the Master Production Schedule for end-items, and from the product structures and the item production lead times. The lead time to be used however, differs in a number of respects from the lead times used in the normal MRP-I calculation. MRP-I is used for generating prioritized item work orders to be released to the PU's. However, we are not dealing with that issue here, we must first solve the more aggregate problem of determining the capacity use per PU and the MPS for the next period. For this problem we need a related but essentially different definition of the concept of lead time.

The lead time of a process determines how much earlier an input should be given to the process in order to realize the output at the required time. It tells us how many time units it takes to process the input into the output. Now for the aggregate decision problem we are dealing with aggregate variables such as production levels and product flows units per time unit. The lead time for the aggregate process involved consists of various components.

Components of the aggregate lead time

1) Work in process

An obvious component of the aggregate lead time is of course the flow time of work orders in the production units. For each product item we should therefore know how much time it takes on a average to carry the workorder through the shop, given the workload norms used.

2) Safety stock

A second,less obvious,component is the safety stock which is held in the controlled stock points on the aggregate level. These safety stocks should be interpreted as production output in advance of the actual requirement. As such, they contribute to the production lead time in the system. Thus the safety stocks for an item should be translated into a lead time component by dividing the safety stock by the average demand rate of that item. For items for which the demand is very irregular, or even incidental, such computations will not be possible. However, this is no problem because for these items we should not use safety stocks but safety time to buffer uncertainty in demand. This safety time can be used directly as a component of the lead time.

3) Batch size

The third factor which generates an aggregate lead time component is the batch size used when releasing work orders. Batch sizes also have the effect that items are being manufactured earlier than they are needed. In fact, for regular demand items,average lead created by a batch size can be calculated as half the batch size divided by the average demand rate of that item. For irregular demand items, the lead time component of the batch size used can be determined in a similar way from the batch size rule.

4) Sequencing constraints

The fourth lead time component is related to constraints on the work order release. If such a constraint exists the effect this has is on lead time is that, on average, the workorders are released earlier than required from a delivery point of view.

For each item we should determine the value of these four lead time components and add them together to arrive at the aggregate production lead time of that item. Given the production structure (materials requirements relationships between the controlled stock items) we now can derive the required echelon stock for each item from the Master Production Schedule for end items. Similarly, we can calculate the required echelon stock for each capacity type by multiplying each item in the required echelon stock with the amount of capacity required per unit, and by summation over all items. These two sets of requirements can be compared with the actual echelon stock to check the realizability of a particular Master Production Schedule.

In using echelon stocks and stock norms,we totally neglect information on the various ways in which multi-purpose materials, component and capacity can be tied up in higher level items. Thus,it is assumed that these items are used in balanced way, accordingthe echelon stock norms for these higher level items. In fact, this real aggregate to approach to measuring the state of the system assumes that detailed procedures exists which take care of this balancing process, so that it is allowed to rely on these aggregate figures for the coordination activities of the Master Planning. In our approach this balancing process is carried out by the Materials Coordination function.

The Master Planning function in fact consists of balancing, for the controlled stock items and crucial capacities, the actual echelon stocks with the echelon stock norms that follow from the current MPS. Monitoring this control process requires that we can distinguish between the various factors which affect this balance, and that we can measure and evaluate their behaviour over time. In the following paragraph we give an outline of a monitoring procedure for the Master Planning process.

Monitoring the dynamic behaviour of echelon stocks

First, consider a production system that produces according to a static MPS, that is, an MPS that is not up-dated with time. For simplicity we consider the capacity echelon for stock for an arbitrary capacity type and introduce the following variables:

$M(t,\tau)$ = the amount of capacity required for the items which, according to the MPS that is valid at time t, are to be delivered in period $t+\tau$. Since we here consider a static MPS we have $M(t,\tau) = M(t+k,\tau-k)$ $k = 0, \dots \infty$. For ease of notation we will refer to $M(t,0)$ as $M(t)$.

$R(T,\tau)$ = the amount of capacity required for the items which, according to the MPS that is valid at time t, are to be released for production in period $t+\tau$. Again in the static MPS case, we have $R(t,\tau) = R(t+k,\tau-k)$, $k = 0, 1, \dots\infty$. We refer to $R(t,0)$ as $R(t)$.

$U(t)$ = the amount of capacity that is decided to be used during period t (a decision variable).

$P(t)$ = the actual amount of capacity used during period t.

$D(t)$ = the amount of capacity required for the items which are actually shipped out of the system during period t (the actual demand).

$AC(t)$ = the actual echelon capacity stock in the system at the start of period t

$RC(t)$ = the required echelon capacity stock in the system, according to the MPS at the start of period t.

Differences between required and actual echelon stock must come from one of the following three sources.

a) differences between actual shipments and the required shipments according to the MPS. For each period this results in a difference denoted by DD(t):

$$DD(t) = M(t) - D(t)$$

b) differences between amount of capacity that is to be used according to the MPS, and the amount of capacity that is decided to be used during period t, referred to as the planned deviation PD(t):

$$PD(t) = R(t) - U(t)$$

These planned deviations are the result of the capacity-use and capacity-variation smoothing decision.

c) differences between the amount of capacity that is decided to be used, and the actually used capacity, referred to as the unplanned deviation UD(t):

$$UD(t) = U(t) - P(t)$$

The actual used capacity deviates from the decision due to unforeseen events during the period. The workload control system, which works per PU, will feed these events back to the actual release of work orders.

The total deviation, TD(t), that is generated in one period, is equal to the sum of these three components.

$$TD(t) = DD(t) + UD(t) + PD(t)$$

The capacity echelon stock deviation at time t, DC(t), is simply the cumulation over time of the variable TD(t).

$$DC(t) = \sum_{i=0}^{\infty} TD(t-i)$$

By breaking down TD(t) in its components we can also write

$$DC(t) = \sum_{i=0}^{\infty} DD(t-i) + \sum_{i=0}^{\infty} PD(t-i) + \sum_{i=0}^{\infty} UD(t-i)$$

It will be clear that for an adequate goods flow control, it is required that DC(t) is under control,given that the MPS is static and that the variables P(t) and D(t) in essence are exogeneous for the production control, the only way to control DC(t) is via the variable U(t), the decision on the amount of production to be started. This implies that in this case each period the actual deviation should be fed back to U(t). However the variable DC(t) not only contains the planned part of the deviation DD(t) and UD(t), but also the planned deviation, PD(t), which is intended for production smoothing. The planned deviation should of course not be corrected in the next period. Therefore we introduce a new variable FD(t) to denote the sum of the unplanned deviations.

$$FD(t) = DD(t) + UD(t)$$

Finally we introduce a second planned production deviation variable, FP(t), which represents the planned correction of the unplanned deviations.
Thus,each period the planned production deviation consists of two components. One component,PD(t),represents the deviation which is introduced to allow smoothing of the production requirements implied by the MPS. The other component FP(t) is introduced to allow for the (possibly smoothed) correction of the unplanned deviation in FD(t). Thus the balance equation for the total change in the total deviation in one period now is extended to:

$$TD(t) = DD(t) + UD(t) + PD(t) + FP(t)$$

and the capacity echelon stock deviation at time t can be written as:

$$DC(t) = \sum_{i=0}^{\infty} DD(t-i) + \sum_{i=0}^{\infty} UD(t-i) + \sum_{i=0}^{\infty} PD(t-i) + \sum_{i=0}^{\infty} FP(t-i)$$

The causal scheme implied by this set of concepts and definitions is given in Fig. 3. The Figure clearly reveals the mixed feedforward and feedback nature of the decision procedure. Since in this paper we are only interested in structuring the production control decision system we will not discuss the details of the decision rules.
Using this causal scheme we can track the behaviour of the echelon stock deviation over time, and the breakdown in its components. For instance, we can observe the behaviour of the two courses of uncontrolled deviation,DD(t) and UD(t), over time and analyse to what extent it "explains" the behaviour of DC(t). Also we can observe any systematic behaviour in DD(t) and UD(t), for instance a mean value which significantly

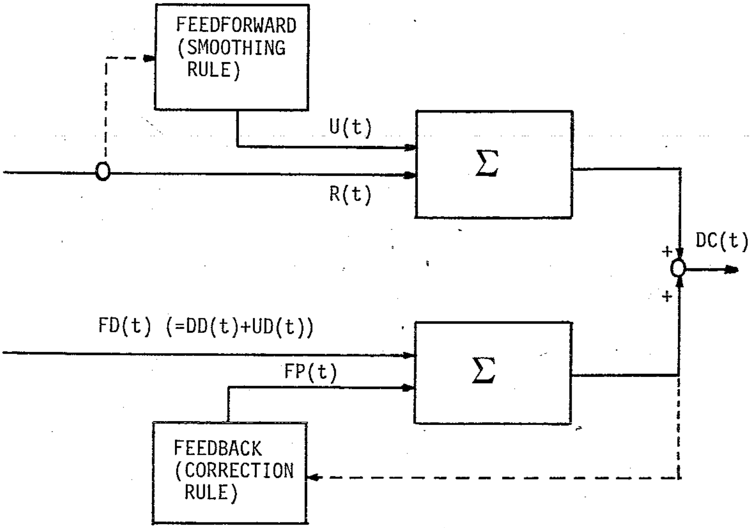

Fig. 3. Causal scheme for the dynamics of the echelon stocks deviations with a static MPS.

differs from zero, and feed this information back to other control areas such as the Master Production Schedule decision function, or the Sales Department which is responsible for generating customer order corresponding to the Master Schedule. Most important however, is the necessity to be able to distinguish between planned and unplanned deviations, because only the unplanned deviations should be corrected via the feedback loop,whereas the planned deviations should be only affected by the smoothing decision function. This is only possible if we can monitor all these components separately.
The purpose of the design of this monitoring procedure has been to be able to check the extent to which the capacity and materials state of the goods flow is in accordance with a proposed MPS. In fact,if at the start of a period an unplanned deviation exists in either a capacity echelon stock or a materials echelon stock, then the plan is clearly not in balance with the state of the goods flow. Thus the MPS is not realistic. The general demand that a MPS always should be realistic now can be operationally defined as the demand that at each period the unplanned echelon stock deviation is zero. So the unplanned deviation which occurs in each period should be offset in the next period by either a production level variation FP(t), or by change in the MPS, or by a combination of both.

Dynamic Master Production Schedules

Up to now we have discussed only the situation where the MPS is static. In this case the MPS schedule can be kept realistic if all the unplanned deviations can be corrected by capacity use and production variations in the next period. Now, from a costs point of view this may not be the best option in many situations in practice. Therefore, if production variations are only possible or desirable to a limited extent, the MPS should be adapted to be in line with the state of the system. Now let $\Delta(t)$ denote the change in required capacity echelon stock due to a change in the

MPS at time t. Then we can complete the control diagram in Fig. 3 by extending the balance equation and adding a second feedback loop to the echelon stock required in the MPS at time t. This echelon stock can be modelled as the difference between the cumulated required releases and the cumulated required deliveries

$$RC(t) = \sum_{i=0}^{\infty} R(t-i-1) - \sum_{i=0}^{\infty} M(t-i-1)$$

This leads to Figure 4.
Using these balance equations we can monitor the processes controlled by the Master Planning function and can explain the deviations from the various sources.

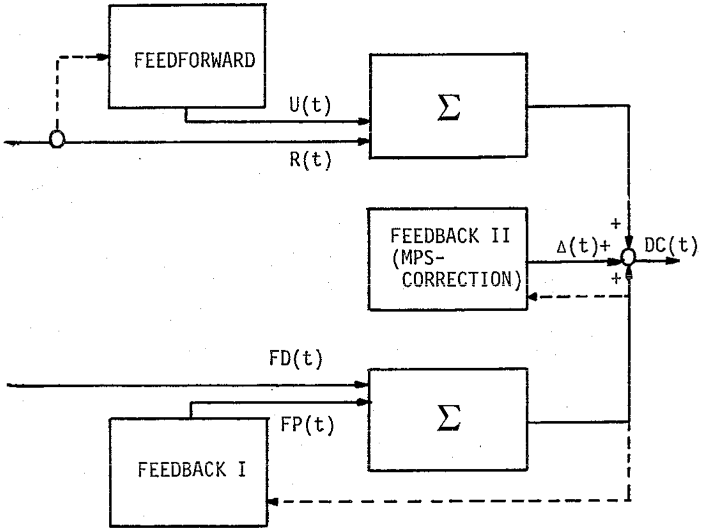

Fig. 4. Causal scheme for the dynamics of the echelon stock deviations with a dynamic MPS.

It will be clear that in our structure the creation of a realistic MPS is still not an easy task, if we consider the fact that for a multi-phase multi-item production system in general this requirement applies to many capacity types and items simultaneously. The only thing we can manipulate in the MPS are the numbers per period per end-item. It is very well possible that for a given situation no MPS can be found which exactly produces expected zero value of the uncontrolled echelon stock deviations. In that case we should just choose the best possible MPS available, and signal the remaining deviation so that we are aware of the extent to which the goods state is out of balance. This remaining imbalance will contribute to the unbalance in actual deliveries to the final stock points relative to the required deliveries according to the current MPS.

Materials coordination

The result of the decision phase described above is that at start of each period we end up with two types of norms to be applied during the next period. First, for each PU, we have generated the required capacity variation and capacity use (in terms of capacity to be transfered into items) to be realized during the next period. Secondly, we have determined an MPS which will be valid during the next period. In the decision process we have guaranteed that these two sets of norms are consistent with the actual state of the goods flow(apart from the deliberate deviation in production we want to apply to each PU because of smoothing requirements). Because these norms are mutually consistent and are also consistent with the state, we can use them to generate actual work order releases during the next period.

However, the actual work order release control does not follow straightforwardly from these two sets of norms. A crucial notion in our design has been the flow time of work orders in the PU, as part of the lead time. The calculation of the echelon stock norms is based to a large extent on norms for these work order flow times. We also know that if capacity is not very flexible, production disturbances during a period may result in realized production which differs from the amount planned (the variable U(t) in our analysis). If we would release work orders according to the level implied by U(t), this would then lead to shifts in the work order flow time. This again would totally incriminate the assumptions on which the previous production level and master production scheduling decision is based. In fact, it would lead to the situation where we would have to adapt the lead times each period and this would result in a very poorly controlled system. Therefore, we require that the workload in each PU is controlled such that the work order flow times can be considered as variables with a constant mean value. This results in the following procedure for generating and releasing work orders at each production unit.

First, based on the average workorder mix and the production level to be applied during the period, a workload norm is calculated. This workload norm expresses how much work in process there should be in the system at any time during the next period. Various procedures exist for calculating such workload norms. At this place, will not go into these details. Then, using the classical MRP routine (now using the classical item lead times and using explicit safety stock levels and batch sizes), for each item a proposed work order release scheme is calculated. These proposed release schemes are frequently updated during a period, to reflect changes in the state of the goods flow which can occur during the period. Because they are generated by an integral MRP system, the proposed workorder releases of the items are coordinated with respect to their time phasing, batch sizing effects, and materials requirements. *Because at the start of the period the MPS has been set taking into account, in an aggregate way, batching, work order flow times, and sequencing constraints, we may expect that during a period there is enough slack in the actual state of the goods flow relative to this MPS, that the detailed proposed schedules generated will not encounter serious materials availability and capacity availability problems.* Thus we may expect that the proposed releases are well implementable, apart from possible production disturbances during the period.

CONCLUSIONS

In this paper we have investigated the problem of how to design a production control structure for multi-product multi-phase production systems. For that purpose we first have introduced the basic concepts items, material, capacity and operation. Next we have introduced the production unit as a self contained production entity which enables us to split up the overal production control problem into a number of product unit control problems and the goods flow control problem. We have analyzed the nature of the goods flow control problem by studying theimpact of the operational constraints per production unit. We have concluded that this problem also needs decomposition, and we have introduced Master Planning to control specific aggregate variables and Materials Coordination for detailing the aggregate decisions, taking into account the operational constraints per PU. Finally, we have introduced capacity and item echelon stocks as state variables for the Master Planning and we have analyzed the process controlled by the Master Planning function to derive the balance equations that can be used for monitoring purposes.

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DISCUSSION AFTER THE PAPER OF J.W.M. BERTRAND

H.J. Pels:

Should the decision hierarchy be reflected in the organizational hierarchy?

J.W.M. Bertrand:

Not necessarilly, organizational position in terms of hierarchy do not generally coincide with decision positions in the production control structure. However, very often the more long term aggregate decisions will be taken by people who are in the higher organizational positions.

J.L. Burbidge:

What are the meaning of your levels of production control?

1. "Master planning" (programming?)
2. "Material control" (ordering?)
3. "Production unit control" (dispatching?)

Are they the same as programming, ordering and dispatching? Please may I have definitions for the terminology project?

J.W.M. Bertrand:

These terms are clarified, more or less implicitly I must confess, in the paper. The meanings are indeed related to some extent to the terms you suggest. However, the differences are in the details. This is caused by the specific control structure developed in the paper which implies differences in the details. To avoid confusion we have therefore introduced new terms.

G. Tidemann-Andersen:

Does the capacity planning in the master schedule emphasise only the bottle-neck resources?

J.W.M. Bertrand:

Yes, but we not only consider bottle-neck capacity but also crucial materials. The types of capacity and materials which are crucial may change over time. Therefore, we use predictive models of the process to be controlled, in order to be able to identify changing bottle-necks (which will result in deteriorating predictive quality of the model).

J.L. Burbidge:

What is Echelon Stock?

J.W.M. Bertrand:

The total amount of an item in the production system considered, be it as work-in-process, as stock, or as part of the work-in-process and stocks of the higher level item of which this item is a part. (See Peterson and Silver's book on Inventory and Production Control, 1979 and also the book of Arrow, Karlin and Scarf: Studies Applied Probability and Management Science, 1962).

MODELLING PRODUCTION MANAGEMENT SYSTEMS
P. Falster and R.B. Mazumder (editors)
Elsevier Science Publishers B.V. (North-Holland)

INFORMATION SYSTEMS FOR HIERARCHICALLY STRUCTURED PRODUCTION CONTROL

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Management Science
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The Netherlands

Current information systems for multi-product multi-phase production situations are mainly focussing on one level of control, viz. the materials coordination level.
In this paper, we assume the existance of two other control levels, viz. a Master Planning level and a shop floor control level within production units. For decision support in such a hierarchically structured control system the data model employed by the information system should be extended. The paper discusses some extensions, especially with respect to an explicit modelling of production units and to explicit feature/option concepts in the bill of materials.

1. INTRODUCTION

The hierarchical nature of control

Many production and inventory control systems are hierarchically structured. However, this structure is quite often not reflected in current information systems. Consequently, there exists tension between the employment of these information systems at different levels of control. In this paper, we shall try to characterize the nature of information systems for different levels of control and to present guidelines for design. We shall refer to multi-level decision-making in the area of production and inventory control for short as production control.

In order to demonstrate the points mentioned it might seem natural to follow one of the well-known production control systems such as MRP II systems. However, these systems suffer precisely from the drawback that requires improvement: MRP II shows a substantial bias on one level of control (viz. the level supported by Material Requirements Planning); both the theory and the software still have a long way to go before real hierarchially structured goods flow control is attained. We shall return to this point in Section 2.
Therefore, this paper is based on a three-level structuring developed in Bertrand [3]. These levels are:

1. Master planning
   At this level, capacity-levels and production levels of various production units are established. Bertrand [3] describes how the decision-making proceeds, facing predicted demand fluctuations and unpredictable disturbances. The decision-making process results furthermore in a Master Production Schedule (MPS) for designated items.
2. Materials coordination
   At this level, decisions are made on production orders to be released to production units. Obviously, the aim is to have all materials to be consumed available at the time of release, with low inventory investment, and while maintaining some flexibility to deal with unpredicted demand fluctuations and other disturbances.
3. Production control within one production unit
   Bertrand [3] , following Plossl and Welch [12], and Wight [13], stresses the fact that the amount of work released to each production unit should be controlled,