The structuring of production control systems

THE STRUCTURING OF PRODUCTION CONTROL SYSTEMS

by

J.W.M. Bertrand
J. Wijngaard

Report ARW 03 THE BDK/ORS/84/10

Eindhoven University of Technology
Department of Industrial Engineering
and Management Sciences
Postbox 513
5600 MB Eindhoven
Netherlands

ABSTRACT

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. From the perspective of Goods Flow Control the PU's are black boxes having certain operational characteristics. The objective of Goods Flow Control is to realize a certain delivery performance, taking into account the PU-operational constraints. The main elements in the Goods Flow Control structure as developed here are Master Planning, Material Coordination, Workload Control and Work Order Release.

1. 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 acitivities 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. A structural (hierarchical) approach is needed to resolve this conflict (see Meal [1984]).

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. Jönsson [1983], Axsäter and Jönsson [1984]). In this paper we stress the general problem of how to structure the complete production control process. 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 is guaranteed and the actual control performance can be measured and therefore can be monitored. This approach has been used in a previous research project on production control in a production unit (see Bertrand and Wortmann [1981]) and is now applied to a more complex production problem including goodsflow control. The concepts used in this approach are partly based on certain concepts from Manufacturing Resources Planning (MRP-II).

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 market needs and production possibilities (see e.g. Berry, Vollmann 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 aim 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 principle we can distinguish three basic sources of inflexibility that are 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 structure of the production control system.

2. SYSTEM BOUNDARY

We assume that for any production control problem in practice a system boundary can be determined. The system boundary defines what "part of the production world" is considered and what part is out of our scope. The system boundary should be established operationally by specyfying the inflows and outflows from the environment into the system considered and visa 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 products to satisfy customer orders, and instructions to change the production capacity of the system. This system boundary concept is illustrated in Fig. 1.

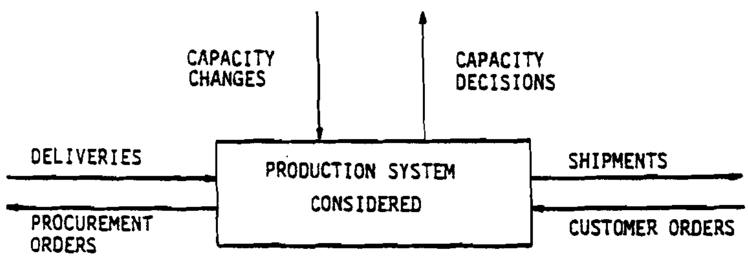

Fig. 1. The boundaries of the production system.

The next step in defining the production control problem is to specify the external and internal relationships of the system. External relationsips 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 is 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 sytem 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 the 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 product.

- the products use shared types of materials and subassemblies
- information on market demand is limited, 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 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 without the scope of this paper.

3. 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 to 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 operations should be related to the scope of the production control problem at hand. The operations generally do not follow straightfowardly from the description of the manufacturing steps, but must be based on the aspect of the system that is addressed by production contro. Now as production control addresses the **timing** of the allocation of resources and materials, a natural criterion for the grouping of manufacturing steps into operations is their relative independence in time. Thus if there is little freedom in relative timing within 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 aggregate 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:

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

In order to simplify the control problem to be solved, an operation is defined such that the time phasing of materials and resources required during the operation is 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 statistic entity.

4. 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 tiem, then the PU may want to work with specific batch sizes. Moreover, if 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 a 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 (especially the delivery performance). 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 promisses 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 conditions per PU imply more stability than 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 efficiency. 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.

5. 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 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 these 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 throughput 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 releases 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 single production phases. Then, for Goods Flow Control, the production processes for end-items 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

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, this influence refers to the timing of work order 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, subassembles, etc.) from the stock points and the input of items to the stock points. 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. We refer to these manufacturing states as **controlled stock items** of the 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 costs.

6. LOCATION OF CONTROLLED STOCK-POINTS

The selection of the controlled stock points in a production system should, among other things, depend on the differences in production status and demand status information available at different points in the production system. For instance, for components used at a low level in the product structure, production or procurement should be based on demand information over a relatively long lead time (the stacked manufacturing lead time of the item). This leads to a relatively high demand uncertainty for these items. Nevertheless, each period production has to be initiated, and generally the amount to be produced is based on a plan (to be discussed later in this paper). The demand uncertainty is buffered then by some slack factor (safety stock or safety time). For items at a high level in the product structure the stacked manufacturing lead time can be quite small, and production can be based on short term demand information. Often, short term demand information is very reliable because it can be based on customer orders on hand. In general the demand uncertainty increases with the stacked lead time of the product item considered. Therefore, in principle, the "amount of production" in each production phase may differ from the amount of production started previously in an earlier phase. For this reason, ideally, we should distinguish as many controlled stock points as there are product-items in the production structure. However, this would create a very complex production control problem. For this reason in practice we prefer to locate controlled stock points at places in the production structure where a substantial change occurs in the demand or production uncertainty. A very common example of such a controlled stock point situation is the use of a decoupling stock between the manufacturing of components according to a plan and the assembly of end-items to customer demand in a make-to-stock, assembly-to-order production sytem

In fact this is a very simple example involving only one level of controlled stocks. In principle in a multi-level production system it may be necessary to distinguish various such controlled stock points or decoupling points, where the use of items out of these stock-points is driven by a different part of the "delivery plan" for end-items. Moreover if the level of standardization of items in the production structure varies a lot (some components may be unique for one end-item type, other components may be standard items, used at many places in many end-items) the relative production uncertainty will be a combined effect of demand uncertainty, stacked item lead time and item level of standardization. This makes the location of controlled stock-points a very complicated matter, which is directly related to the Master Planning decision function (to be discussed later). In particular large differences in production uncertainty lead to the need for a multi-level Master Planning decision function. This is a very important research topic, which we expect to get ample attention in the next decade.

Finally it should be mentioned that apart from differences in demand uncertainty, also large differences in production uncertainty will give rise to the need for controlled stock-points. A very prominent factor which leads to differences in production uncertainty is a variable yield of the manufacturing process. For instance in integrated circuits manufacturing, production phases exist where the yield of the manufacturing process per batch has an average of 50% with a 20% standard deviation. Thus for the product item before this manufacturing stage, a large uncertainty exists with respect to the result of the process after this stage, which uncertainty is largely reduced if the actual yield has been measured upon completion of the batch in thatphase. In this situation also, a large change in uncertainty occurs at a specific place in the production structure. Therefore, that place in the production structure (after the manufacturing phase with the high yield variance) should be considered as a candidate for the location of a controlled stock point.

7. PU 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 constraints reflect 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. These constraints reflect 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 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 decreases the flexibility of the PU because, on 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 work orders 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 calculations 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 througput 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 released or which are released later. 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 PU 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 (see section 9).

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 possibility and concentrate on the coordination problem.

8. GOODS FLOW CONTROL STRUCTURE

Considering the huge complexity of Goods Flow Control (GFC) which follows from the previous analysis, it will be clear that finding a general optimal control is impossible, even for a production system of moderate complexity and for a static situation. We propose to decompose Goods Flow Control into the following four parts:

1) Master Planning
2) Material Coordination
3) Workload Control
4) Workorder Release

See figure 2 for a first rough indication of the relationship between these levels of control.

The Master Planning level forms the connection with the higher levels of control in the production organization, where the various aspects of the organization (logistics, quality, finance, manpower, etc.) are integrated (Management Control, Anthony [1965]). Workload Control and Workorder Release lie in the interface of Goods Flow Control and Production Unit Control.

Two elements are crucial in this decomposition, namely

a) the coordination of Sales and Manufacturing
b) the interference of capacities and products.

These two elements will be discussed in the next two sections. In section 11.3 the complete Goods Flow Control structure will be discussed.

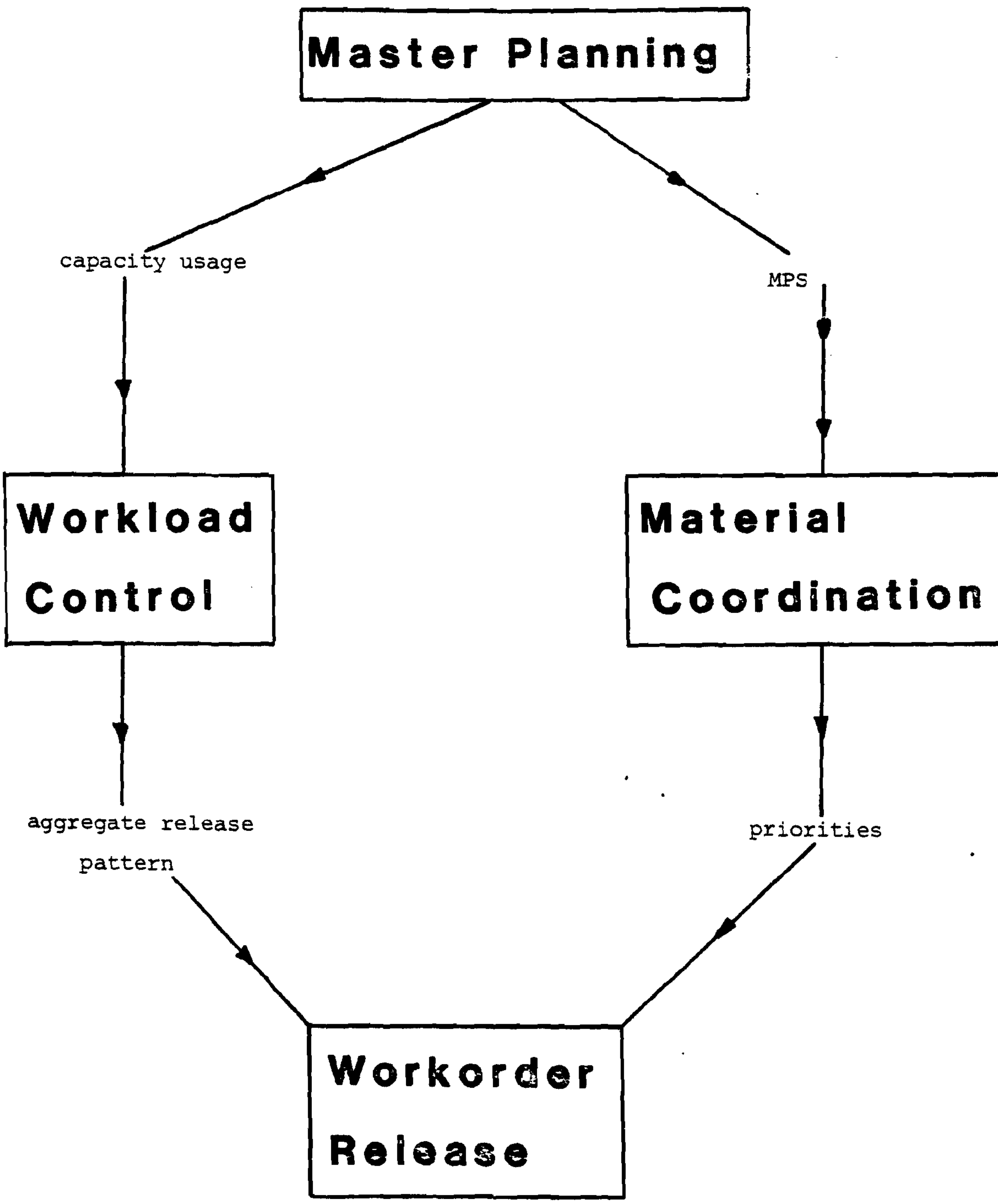

Figure 2: Sketch of Goods Flow Control Structure

9. COORDINATION OF SALES AND MANUFACTURING

Within each production system one has to distinguish the functions Sales and Manufacturing. Sales generates demand and accepts commitments with respect to customer deliveries. Manufacturing has to realize the required deliveries. Coordination between these activities is required. There have to be aggregate agreements with respect to service performance, stability and reliability of required delivery patterns, total accepted demand, etc. This we call **structural** coordination, the coordination affects aggregates and averages.

Structural and operational coordination

If there is only structural coordination Sales determines required delivery patterns, taking into account the aggregate agreements, but neglecting the actual state of Manufacturing. In such a situation the required deliveries can be interpreted as autonomous demand. In many cases, however, improvements can be expected from also taking into account the actual state of Manufacturing in the coordination process. This implies **operational** coordination. In the MRP-II framework this type of coordination is incorporated in the concept MPS (Berry, Vollmann, Whybark [1979]). However, in that framework the MPS serves two purposes. It is not only a realistic (potential) delivery plan based on the structural and operational coordination of Sales and Manufacturing, but it also is the basis for coordinating the various production units in the system by netting and offsetting. In current MRP literature these two functions of the MPS are not well distinguished. In this paper we will formalize this distinction and interprete the MPS as a (potential) delivery plan based on state information with respect to both Sales and Manufacturing.

Sales flexibility

Including state information with respect to Manufacturing in the MPS makes only sense if Sales can use the information. This is the case if there exists a certain flexibility at the sales side. Such sales flexibility could be for instance the possibility to influence customer order due dates, the possibility to start short term sales promotion, etc. Another source of sales flexibility exists if sales controls to some extent the inventories in the distribution stages. However, also if sales flexibility is very limited it can be benificial to have an MPS including information on the state of Manufacturing. For instance if due to some manufacturing problem shortages are inevitable, it makes it possible for Sales to distribute the shortages over the various product types or customers.

In situations where sales flexibility is very small the MPS can be interpreted as "demand", that is, as an objective for Manufacturing. In cases where there is much short term sales flexibility the MPS represents also the state of Manufacturing and can be interpreted as objective for Sales as well.

Form of the MPS

An MPS is a sequence of vectors or a matrix (quantities/period of the MPS items). It will be clear that such a matrix is a rather poor representation of the combined state of the Manufacturing and Sales process. A better state representation would be a set of **trajectories**. For Manufacturing these trajectories would pertain to the set of **realizable** delivery patterns; for Sales they would pertain to the set of **acceptable** delivery patterns, where the term acceptability refers to the possibility to realize certain sales patterns. The objective of both Sales and Manufacturing would then be to realize a non-void intersection of these two sets of trajectories.

However, we should keep in mind that these state variables can only be realistically described in stochastic terms, as the real future deliveries and sales not only depend on the current state and the future control decisions, but also on a number of uncontrolled stochastic variables. Therefore we accept the convention of using one single delivery pattern as state representation of both Manufacturing and Sales. This pattern may (informally) be interpreted as a more or less arbitrary pattern in the above mentioned intersection of sets of realizable delivery patterns and acceptable delivery patterns. From this discussion it will be clear that the relationship between this MPS and the real state of the system cannot be formalized. However, in situations where the flexibility of Manufacturing and Sales and the procedures to coordinate both are quite stable, we may expect that the participants in this coordination process will generate implicit stable and consistent models of this relationship.

Generally the MPS is established periodically and is intended to be valid during the following period. The discussion above makes clear that each new MPS may differ from the old one. This because of all kinds of uncontroled stochastic variables with respect to Sales as well as with respect to Manufacturing, which have occured during the period, and which are accounted for in the new MPS. By not adapting the MPS a high Sales or Manufacturing flexibility would be presupposed and this flexibility would be used in a very rigid and probably non-optimal way.

10. INTERFERENCE OF CAPACITIES AND PRODUCTS

To illustrate the relationship between capacities and products in Goods Flow Control we consider a production system with autonomous demand (no sales flexibility). The difficulty of having an MPS instead of demand has been discussed in the previous section. In the next section both difficulties are combined and complete control structures are described.

In situations with autonomous demand the objective of GFC is to realize a certain service performance. This has to be done by controlling work order releases to PU's and by adjusting capacities and capacity usage of PU's. The decision freedom for GFC to manipulate these variables and to vary the inventories in the controlled stock points have to be "budgetted" by higher levels of control. This also includes the restrictions on the variables imposed by the batching and sequencing constraints (see section 7).

In controlling the Goods Flow we face disturbances and fluctuations with respect to

- procurement leadtimes
- production leadtimes
- capacities
- yield
- demand

- registration of inventory and work in process.

In general it is important to put effort in reducing these fluctuations and disturbances or in making them more predictable. The current drive in industry for realizing short lead time, high quality (zero-defect) and just-in-time production therefore should be highly valued. However, in many situations in practice the possibilities in this respect are limited, sometimes because of technical constraints, sometimes because of economical constraints. On top of that, the capacity flexibility may be to small to cope with the remaining variability, be it predictable or unpredictable. For many situations inventory buffers are necessary to absorb the state variations due to the gap between flexibility and variability. Using inventory buffers in the right way can be an effective and efficient way to absorb short term variability.

Inventory as stored capacity

A weak point of using inventory buffers to absorb production and demand fluctuations is that inventories only can be realized as quantities of specific items, while most types of fluctuations are directly or indirectly related to capacity availability. Fluctuations in produciton leadtimes for instance are partly due to disturbances in capacity availability. But also fluctuations in demand for a certain product have a capacity dimension. To some extent, inventories of other products can be used to absorb these fluctuations. In short, inventory of specific products has the property that it also can be used as **stored capacity.**

We will clarify this point with a simple example. Consider a make-to-stock situation with one production stage and two products which have identical production and demand characteristics. Compare a state with inventories

$\{I_1, I_2\}$ with a state with inventories $\{I_1 + x, I_2 - x\}$.

On a short term these states are different with respect to the risk of stockout. On a somewhat longer term, however, the states are equivalent in this respect. The term at which the states are equivalent corresponds to the term at which for both products production has taken place. On that term the effectivity of the buffer for absorbing capacity and demand fluctuations depends only on the **total** inventory. Also, fluctuations in demand for product 1 or product 2 are equivalent on that term. One can cope to the same extent with both types of fluctuations. On that term one, irrespective of the detailed state of the inventory.

Two control levels

The above example shows that on a somewhat longer term the inventory of products with regular demand can be considered as being just stored capacity. This term is roughly equal to the production cycle time, that is, the term at which all products with regular demand have been produced at least once. In many situations the production cycle time is much shorter than the term at which capacities can be changed. That makes it possible to distinguish two levels of control. Capacity decisions can be decomposed from detailed inventory control and workorder release. In many cases, i.e. where constant work order throughput times are a prerequisite for adequate control, capacity usage is determined by capacity (see Bertrand/Wortmann [1981). In other situations it is possible in principle to vary capacity usage without varying the capacity. In such situations work-orders are directly coupled to customer orders and internal work-orders throughput times may be related to customer order due dates. However, in such situation, if the PU's operate at a high utilization rate, such independent variations of capacity usage have a long lasting impact on mean work-order throughput times. For that reason, also in these cases it makes sense to integrate capacity decisions and capacity usage decisions.

This kind of decomposition has been investigated and discussed for instance by Van Beek [1977], Meal [1978] and Bemelmans/Wijngaard [1982]. On the capacity/capacity usage level one uses only capacities and capacity aggregates as variables. Demand, production and inventory are all aggregated to capacity. Results with respect to capacity usage are used as budgets at the second level. The capacity usage has to be allocated then to the various products. A good objective for the second level of control is to keep the expected run-out times of the individual products as much as possible equal (taking into account of course the batching and sequencing restrictions). At this level detailed short term information has to be used. Because of production and demand variations, and because of the operational constraints of the PU's it is not possible to realize completely equal run-out times.

The remaining degree of imbalance in run-out times can be considered as the control performance of the second level and has to be taken into account at the first control level: at the first level extra inventory (slack) should be provided to allow for this imbalance.

The effectivity of such a decomposition depends on the extent to which the performance of the second level decision process is independent of the decisions made at the first level. Independence is high in case of rigid capacities and high utilization rates.

It should be noticed that slow moving products (slow-movers) should be excluded from this hierarchical method of control. This because slow-mover inventory is not very effective as stored capacity. Including slow-movers would increase the production cycle time significantly. Thus the problem remains of how to deal with slow-movers in this approach. A straightforward and very effective possibility is to give slow-movers high priority at all levels of decision making and to adjust the capacity availability by decreasing it with the capacity required for the slow-movers (for details on this approach see Bemelmans [1985]).

Decomposition can also be applied to multi-stage production situations (see Wijngaard [1984a]), although in that case the relationship between the capacity aspect and the product aspect is more intricate (see also the remarks in section 7). In this case for each product-item of a PU the horizon for the second (detailed) level of Goods Flow Control has to be increased with the total production lead time (the stacked item lead time).

The product oriented approach

An attractive alternative for the capacity oriented hierarchical approach discussed above is the product oriented approach. In the product oriented approach the capacity usage decisions are not integrated with the capacity adjustment decision. Capacity usage is integrated with capacity allocation. These decisions are decomposed along the products; all products are controlled separately. The interference with other products because of restricted capacities is modelled as a stationary extension of the production lead time in the PU.

This interference is revealed at the work-order release level. In situations with a stable utilization rate such a product oriented approach works just as well as the hierarchical approach (see Bemelmans/Wijngaard [1982]). It is possible then to use queueing type analyses to estimate the delays due to the interference of products because of restricted capacities (see for instance, Williams [1984]). But in case there is no stable utilization rate the product oriented approach may not be expected to work well. Decisions with respect to capacity changes have to be based on the effect of these changes at the lower level of control. The only effect which can be taken into account easily in this product oriented approach is the influence on utilization rate and via utilization rate on interference delays. This makes only sense if each capacity change leads to a new stationary situation. However, if a PU works at a high utilization rate, the transient times are long and it will take much time before a new situation is established. Thus if capacities are changed frequently it is necessary to control (aggregate) inventories and capacities simultaneously. The product oriented approach does not fit then.

At this place it has to be mentioned that in the earlier mentioned hierarchical approach the slow-movers have to be controlled product oreinted. However, the capacity usage of slow-movers is generally so small that there are hardly no delays due to interference on the restricted capacities. This implies that with the capacity-oriented hierarchical approach we have none of the problems that are typical for the product oriented approach.

The integral detailed approach

Up to this point we have discussed two ways to decompose the complete problem of controlling capacities, capacity usage and individual product inventories. Our premises have been that the complexity and the stochasticity of the problem makes a decomposition approach unavoidable. However in simple and more deterministic cases the use of an integral approach may be realistic, possibly restricted to the main products. An integral model of the production control problem, including decision variables, state variables and goal variables, can then be built, and the solution of this model can be realistically implemented in practice. In that case also it is generally necessary to use a kind of decomposition but this time the term decomposition refers to techniques to solve the integral model (i.e. decomposition techniques applied to large scale mathematical programming models). See Billington, et al. [1983] for a sketch of such an approach. This type of decomposition (problem decomposition) should be distinguished carefully from the decomposition approach applied to decision making processes which we discuss in this paper.

11. THE COMPLETE CONTROL STRUCTURE

The GFC structure has to depend on
- the flexibility of the sytem
- the objectives
- the characteristics of the environment

The flexibility of the GFC system is determined by the operational relationships of the Production Units (see section 7) and by restrictions (budgets) with respect to inventories, make-or-buy decisions, capacity changes, etc. The objectives of the GFC system are norms and restrictions with respect to service performance. Characteristics of the environment refer to procurement characteristics, customer behaviour, yield (product and production quality) behaviour of capacities (as far as not controllable by GFC).

It has to be mentioned that the distinction between an objective and a restriction of the system is rather arbitrary. For instance an inventory budget could be interpreted as an objective. However, we choose not to do so. We consider timely delivery as the objective function of GFC and the possibility to vary inventories as one of the means for realizing this.

To guarantee an adequate control structure and to realize consistent restrictions and objectives it is necessary (at design level) to monitor and control flexibility, objectives and environement characteristics. It is important to notice that flexibility is not given but is partly the result of the definition of production units and the design of Production Unit Control. At GFC level production units are characterized by operational constraints and norms.

Flexibility within the production units gives the possibility to keep the characteristics rather simple (see section 5, see also Simon [1981]). This helps keeping GFC simple.

The introduction of production units with rather simple operational constraints and performance norms reduces the variety of GFC systems. However, the variety is still to high to allow for one uniform structure to be applied to all possible situations in practice. Therefore, we will present two closely related structures which cannot be used in all situations directly, but which can, in most situations at least, be used as a starting point in the design process. The difference between the structures is due to different production unit characterizations. In both structures, however, we distinguish four levels of control:

- Master Planning
- Workload Control
- Material Coordination
- Workorder Release.

In the next two subsections both structures will be discussed and the character of the four functions will be described.

11.1 PRODUCTION UNITS WITH RIGID CAPACITY USAGE

The first type of structure is intended for cases where the capacity usage of the production units is difficult to change (e.g. complex Job-Shop type production units). To keep the performance of such production units predictable, the mean throughput time and utilization rate should be fixed (see Bertrand/Wortmann [1981]). That means that the available capacity determines the capacity usage (= throughput).

The basic structure we propose for this kind of situation is sketched in Fig. 3. The function of **Master Planning** is to control capacity variations (and hence variations in capacity usage) and the aggregate MPS. The capacity aggregates determined by Master Planning serve as restricitions for **Material Coordination.**

The function of Material Coordination is to disaggregate (allocate) the aggregate flows so as to get a good balance of the individual inventories. The relationship between Master Planning and Material Coordination is as described in section 10. The performance of Material Coordination in such a structure is not expressed in terms of customer order delivery performance, but is related to the balance of the individual final inventories (or backlogs). At Master Planning level an estimate of this performance should be available to be able to realize aggregate inventories such that the delivery performance for each of the individual products is sufficient. Two important factors influencing the performance of Material Coordination are batching restrictions and sequencing restrictions.

Workload Control and **Workorder Release** are functions at the interface of GFC and Production Unit Control. The output of Workload Control is the aggregate release pattern. Workorder Release concerns workorders of individual products. Coordination with Production Unit Control is necessary because of preferences with respect to the production progress in the Production Unit.

We will consider each of these functions now in more detail.

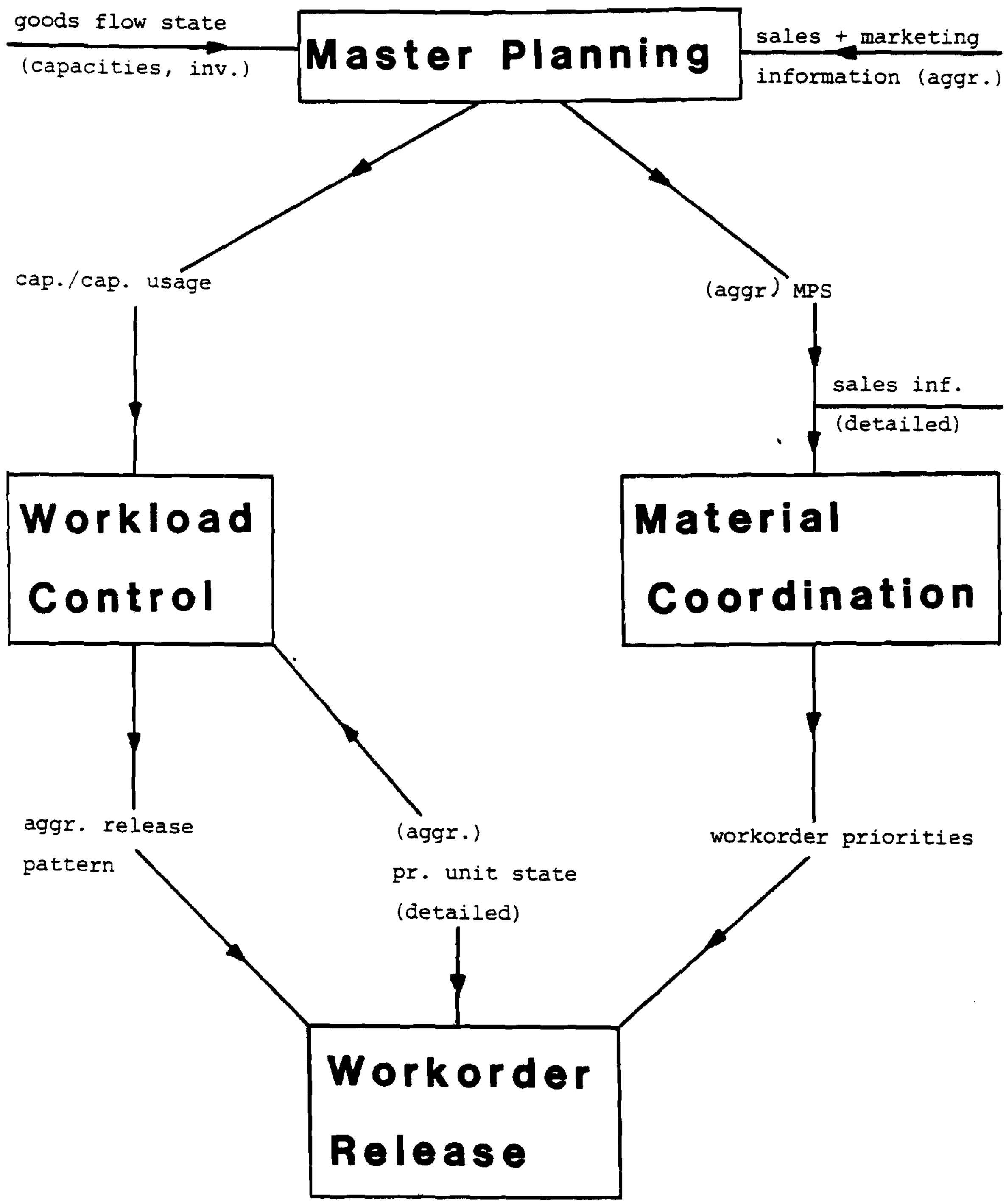

Fig. 3: Goods Flow Control structure in case of inflexible capacity usage.

Master Planning

The aggregates to use at Master Planning level are capacity aggregates. This is easy as long as there is only one relevant capacity dimension and the products have almost identical characteristics. In such cases capacity usage patterns and an aggregate MPS are sufficient to project future expected aggregate inventory patterns.

This may become more difficult if there are more relevant capacity dimensions. It is necessary then to estimate the capacity content of the inventories for all relevant capacity dimensions. This can be done by controlling the MPS in a more detailed way or by using fixed ratios of capacity requirements on different capacity dimensions. This is equivalent to aggregating the bill of capacity. The possibilities to use such aggregate capacity bills in the Master Planning process have been investigated by Axsäter and Jönsson [1984]. The stability of the MPS over the various products is important in using such aggregate bills.

Another difficulty with respect to aggregate Master Planning is due to the existance of slow-movers or, more general, products with irregular production. As explained already in section 10, such products should not be included in the aggregate decision variables. A possible solution is to aggregate only over products with regular production and give the other products a high priority at all levels of decision making. The slow-movers are completely controlled then by Material Coordination and the control performance of Material coordination with respect to these products is the delivery performance itself. The aggregate release pattern for fast-movers has to be adjusted for the releases of work-orders for slow-movers.

It is difficult to construct suitable decision support models to support the Master Planning function. An important reason for this is that it is difficult to formalize the sales flexibility (see section 9). The MPS is the output of a coordination process of Sales/Marketing and Manufacturing. Given the current definition of a Master Plan, the procedures of this coordination process can be formalized, but not its content. As long as sales and marketing flexibility cannot be formalized in an operational way it is only possible to support the capacity (usage) determination of Master Planning by models in which the MPS is treated as autonomous demand. And even then the models may become highly complex because of the behaviour of the MPS as a function of time (stability, reliability) and because of the multi-stage, multi-capacity aspect of the production situation. However, one could try to use HMMS-rules, linear programming-based or control theory type of decision rules, and evaluate by means of numerical analyses or simulation how such methods work for certain typical situations. Evaluation has to be based on variation in capacity usage and inventory variation (see for instance Bertrand [1984]). The influence of the planning horizon could be one of the points of interest here (see Bemelmans [1983]). See also Silver [1972], Boskma [1979] for reviews of models which can be used to support the Master Planning function.

Material Coordination

As already mentioned the function of Material Coordination is to balance the final inventories of the various products. The capacity usage determined by Master Planning serves as a budget. Slow-movers, however, are excluded from this hierarchical approach and are controlled completely at Material Coordination level.

It is important to notice that at the Material Coordination level it is possible in general to use more actual and more detailed sales information than at the Master Planning level. Master Planning and Material Coordination may have different review periods and the sales information used by Material Coordination is detailed and updated compared to the aggregate sales information used by Master Planning.

Models to support Material coordination are infinite capacity safety stock models (see Wortmann/Wijngaard [1984]) as far as products with irregular production are concerned. For products with regular demand one needs models to estimate the effect of certain release policies on the imbalance of final inventories. Constructing useful models of this last kind is rather easy because the imbalance of the final inventories is rather insensitive to capacity variations and changes in predictability (see Wijngaard [1984b]). This makes it even possible to use small scale simulation models to get complete results for this control aspect.

Workload Control

In the type of situation considered here the throughput time is assumed to be determined at a higher level of control. That means that capacity, capacity usage and workload norm are coupled. Applying this workload norm means that the aggregate release pattern depends also on the way the Production Unit is controlled. The actual aggregate release depends on the actual state of the Production Unit. See also the remarks on feedback in section 7.

Workorder Release

Material Coordination determines detailed (dynamic) release **priorities** taking into account the (static) restrictions with respect to batching and sequencing. However, the preferences of the Production Unit cannot be described completely by such static restrictions. Think for instance of the actual availability of specialized personnel. That means that in general the actual work-order releases will be the results of a coordination process of Material Coordination and Production Unit Control. The actual state of the production unit will influence what is going to be released. This also will affect the performance of Material Coordination (the balance), just as the sequencing and batching restrictions affect this performance. At the Master Planning level this effect has to be taken into account as well.

10.2 PRODUCTION UNITS WITH FLEXIBLE CAPACITY USAGE

The second type of structure is intended for situations where the capacity usage can be varied at the same term as the capacity allocation. For instance, a production unit dominated by one machine where the capacity is difficult to vary but where because of a high flexibility of machine personnel the capacity usage is easy to vary. In these cases one may speak of production unit utilization while in the previous subsection one could only speak of machine utilization.

The basic structure appropriate for this kind of situation is shown in Fig. 4. The structure is based on a product-oriented decomposition approach.

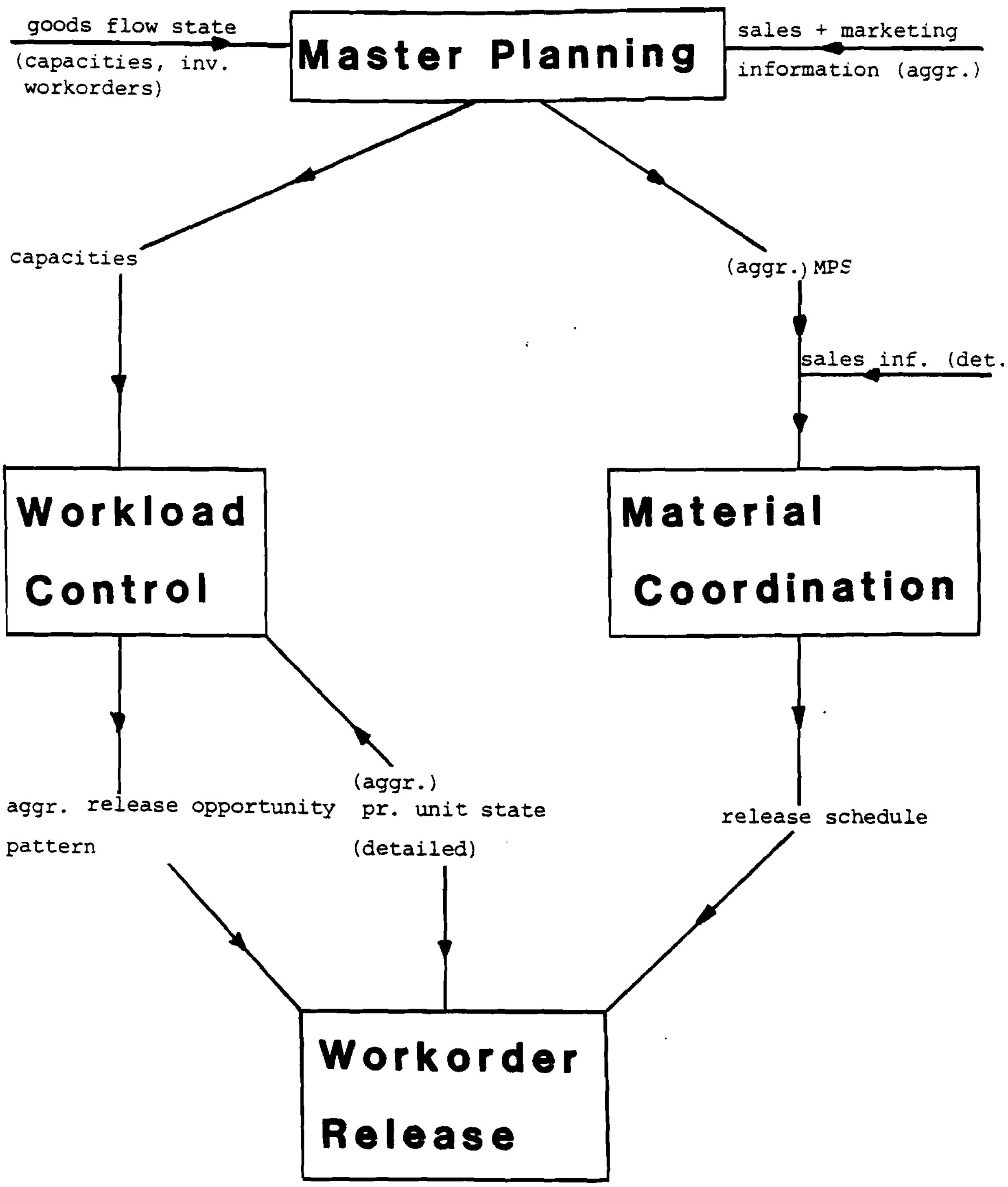

Figure 4: Goods Flow Control structure in case of flexible capacity usage. Product oriented.

In section 10 it has been argued already that a product oriented approach works well in case of a low utilization rate or in case of a higher but stable utilization rate. It is essential that delays due to interference of work-orders competing for the same restricted capacity can be described as independent stationary delays.

In this structure **Master Planning** has to determine capacities and an (aggregate) MPS such that the utilization rates of the production units are stable. A detailed MPS is based on the aggregate MPS and new additional sales information. **Material Coordination** has to realize a satisfactory delivery performance for all products. At this decision level the delays due to the interference of products have to be taken into account (average work-order delay and, if necessary, also delay variance). The delays become actual can be estimated by confronting the detailed work-order release schedules, proposed by Material Coordination, with the state of the production unit. Also in this case it is possible to distinguish **Workload Control** and **Work Order Release.** However, in this case the output of Workload Control is not an aggregate release pattern, but an aggregate release opportunity pattern. Instead of a workload norm a maximum workload is used to check the realizability of the proposed release schedules. This maximum workload reflects the maximum capacity use that is possible without violating the work order throughput time norms.

At Master Planning level stable utilization rates can be realized by making medium term (or at least not too short term, say 2-3 months) agreements with Sales with respect to the capacity content of the MPS. The short-term MPS which results may agree not totally with these appointments. However, such deviations can be treated by Material Coordination in the same way as short term variations in case of autonomous stationary demand. The resulting Material Coordination control problem is discussed in Timmer, et al. [1984] and Wijngaard/Wortmann [1984]. This control level in the structure can be supported by MRP-I, Base Stock or SIC models and techniques.

Feedback

The problem with the approach outlined above is that it is hardly possible to check stability. Variables in models may be stationary, but reality is never completely stationary. That means that in order to prevent that the whole system gets out of control, Material Coordination should require that a feedback loop on the number of work orders scheduled is added to the Master Planning control level. So, a kind of workload Control on the total system, simular to the workload control per production unit. In this higher level Workload Control inventories should be interpreted as partly processed products. This feedback loop can be rather weak if the Master Plan is rather stable.

Capacity oriented alternative

The structure introduced above and depicted in Figure 4 is based on a product oriented approach (see section 10). As mentioned in section 10 the product oriented approach and the capacity oriented approach are equivalent in a wide range of situations. In particular, a capacity oriented approach is also possible in situations with short term flexibility with respect to capacity usage. We will investigate how in this case the control structure of Fig. 4 has to be adjusted.

In situations with short term capacity use flexibility the aggregate release pattern follows from the aggregate release opportunity pattern and new aggregate information with respect to sales (see Fig. 5). The difference of this aggregate sales information as compared to the aggregate sales information used at Master Planning level is only that it is more recent. The Material coordination function is (as in subsection 10.1) to balance the individual product inventories. That means that reduction of the review period of Master Planning leads to a structure which is quite similar to the structure depicted in Fig. 3. The difference is that workload and capacity are more loosely coupled and that it is therefore possible to distinguish aggregate release opportunities and aggregate releases. The relationship between Master Planning and Workload Control is different from the corresponding relationship in Fig. 3, the relationship between Material Coordination and Work Order Release with the other functions is the same as in Fig. 3. Trying to realize a stable utilization is not essential in this approach. It is just a very specific type of Master Planning which can be easily replaced by another type of Master Planning.

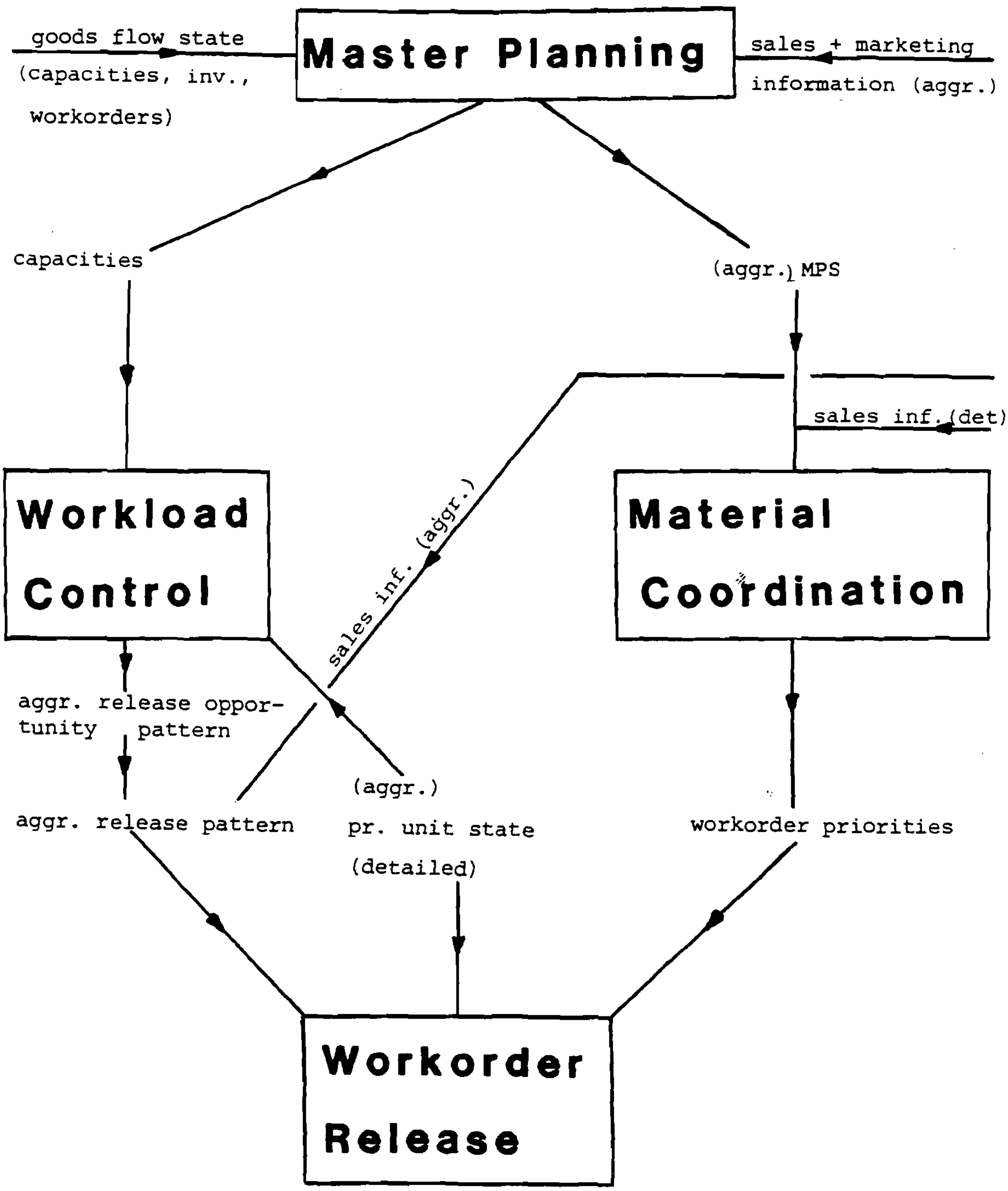

Figure 4: Goodsflow control structure in case of flexible capacity usage. Capacity oriented.

The above discussion suggests that structures as in Fig. 3 are more general applicable than structures as in Fig. 4. This may be so, but many decision support models and techniques fit better in the structure of Figure 4, and there are certainly many cases where that structure fits just as well. Therefore we preferred to give both structures.

12. CONCLUSIONS

Production control is complex. Many decisions interfere with each other and the production control in total interferes with the control of other aspects in the organization (quality, manpower,..). Structuring is necessary to reduce the complexity. However, the structure should be chosen so that not much potential flexibility is lost.

The precise structure to be chosen should depend on the characteristics of the organization. However, there are elements with respect to structure which have a much wider generality. These elements have been discussed in this paper:

* The definition of basic elements as capacities, materials, operations as a first step in the design of the production control structure, instead of considering them as externally given items.
* The introduction of production units and the decomposition of the total production control to Goods Flow Control and Production Unit Control.
* The relationship of Sales and Manufacturing and the interference of products and capacities as two main determining factors of the Goods Flow Control structure.

The generality of these elements makes it possible to develop a small, but relative complete, set of reference structures. For Goods Flow Control in a repetitive manufacturing situation (multi-stage, multi-product) we discussed two such reference structures.

During the last decades the contribution of Operations Research to production control has been quite restricted. On the one hand Operations Research could contribute to solving specific instances of problems in practice. On the other hand Operations Research could contribute to solving rather general but artificially simple theoretical problems. The existence of (more or less) standard production control structures makes it possible to exploit the OR models and techniques much better. The existence of such standard structures reduces the number of relevant OR models. Relevant OR models are models which fit in some standard structure or which can be used to choose between different standard structures.

REFERENCES

Anthony, R.N. [1965], "Planning and Control Systems: A Framework for Analysis", Harvard University.

Axsäter, S. [1979], "On the design of the Aggregate Model in a Hierarchical Production Planning System", Engineering and Process Economics 4, 89-97.

Axsäter, S. and Jönsson, H. [1984], "Aggregation and Disaggregation in Hierarchical Production Planning", European Journal of Operational Research 17, 338-350.

Beek, P. van [1977], "An Application of Dynamic Programming and the HMMS rule on Tow-level Production Control", Zeitschrift für Operations Research 21, B133-B141.

Bemelmans, R.P.H.G., Wijngaard, J. [1982], "A Capacity oriented approach of Production and Inventory Systems", Proc. Second Intern. Symp. on Inventories, 595-607.

Bemelmans, R.P.H.G. [1983], "A Single-Machine Multi-Product Planning Problem under Periodic Review", Report BDK/ORS/83/02, Eindhoven University of Technology.

Bemelmans, R.P.H.G. [1985], "On the Capacity aspect of Inventories", Ph.D. Thesis, Department of Industrial Engineering, Eindhoven University of Technology.

Bertrand, J.W.M. and Wortmann, J.C. [1981], "Production Control and Information Systems for Component Manufacturing Shops", Elsevier Scientific Pu. Co. Amsterdam.

Bertrand, J.W.M. [1984], "Balancing Production Level Variations and Inventory Variations in Complex Production Systems", Report BDK/KBS/84/04, Eindhoven University of Technology.

Berry, W.L., Vollmann, T.E., and Whybark, D.C. [1979], "Master Production Scheduling: Principles and Practice", APICS.

Billington, P.J., J.O. McClain and L.J. Thomas [1983], "Capacity Constrained MRP Systems", Management Science 29, 1126-1141.

Bitran, G.R. and Hax, A.C. [1977], "On the Design of Hierarchical Production Planning Systems", Decision Sciences 8, 28-55.

Boskma, K. [1979], "Medium Term Planning of Production and Sales", Ph.D. Thesis University of Groningen (in Dutch).

Hax, A.C., and Meal, H.C. [1975], "Hierarchical Integration of Production Planning and Scheduling", In: M.A. Geisler (ed.), Studies in Management Sciences, Vol. 1, Logistics (North-Holland-American Elsevier, Amsterdam).

Jönsson, H. [1983], "Simulation Studies in Hierarchical Systems in Production and Inventory Control", Ph.D. Thesis, Department of Production Economics, Linköping University.

Meal, H.C. [1978], "A Study of Multi-Stage Production Planning", Chapter 9 in "Studies in Operations Management", A.C. Hax (ed.), North-Holland.

New, C.C. [1977], "Managing the Manufacture of Complex Products", Business Books, London.

Plossl, G.W., and Welch, W.E. [1979], "The Role of Top-Management in the Control of Inventory", Reston Pu. Co.

Silver, E.A. [1972], "Aggregate Production Planning: State of the Art", Prod. and Inv. Management 1972, 1st qtr., pp 15-40.

Simon, H.A. [1981], "The Sciences of the Artificial", MIT Press, Cambridge, Massachusetts.

Timmer, J.P.J., Bertrand, J.W.M. and Monhemius, W. [1984], "Production and Inventory Control with the Base Stock System", Report BDK/KBS/84/05.

Wijngaard, J. [1982], "On Aggregation in Production Planning", Engineering Costs and Production Economics 6, 259-265.

Wijngaard, J. [1984a], "Aggregation and Decomposition in Logistic Control of Multi-Stage, Multi-Product, Production/Inventory Systems", Operational Research '84, J.P. Brans (ed.), 551-565.

Wijngaard, J. [1984b], "Capacities in Inventory Control", Report BDK/ORS/84/06, Eindhoven University of Technology.

Williams, T.M. [1984], "Special Products and Uncertainty in Production/Inventory Systems", European Journal of Operational Research 15, 46-54.

Wortmann, J.C. and Wijngaard, J. [1984], "MRP and inventories", Report BDK/ORS/84/08, Eindhoven University of Technology.

Zipkin, P. [1982], "Exact Approximate Cost Functions for Product Aggregates", Management Science 28, 1002-1012.