Production control in engineer-to-order firms

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Production control in engineer-to-order firms

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Abstract

During the last decade many engineer-to-order firms have tried to implement MRP II systems, however, the little or no success. The choice of a MRP II system is often based on the wide availability of MRP II software and the fact that the exact reasons why this software is not suitable for engineer-to-order firms are not understood. Therefore, the many implementation failures are not surprising. In the first part of this paper we will discuss the main differences between engineer-to-order manufacturing and the make-to-stock manufacturing (which was the basis for the development of MRP II software). Important characteristics of the engineer-to-order situation are: the important role of the customer order, the customer-specific product specifications, and the product and production uncertainty. These characteristics of the engineer-to-order production situation differ substantially from the basic assumptions of MRP II. An engineer-to-order situation thus asks for a completely different production control system. In the second part of this paper we will present a production control framework which better suits the specific characteristics of the engineer-to-order situation.

1. Introduction

The nature of the production control system depends heavily on the nature of the production situation to be controlled [1,2]. Many classifications have been made with the purpose to distinguish between different production situations. Each distinct type asks for a different production control system. We mention here the classification of Wild [1], New [3] and Sari [4]. These three classification have the following points of view in common:

- the purpose of the classification is to distinguish between different production control situations;
- differences in the production control system can be explained by characteristics of the production situation in relation to the environment (i.e. the market).
- the distinction is primarily based upon the nature of customer orders and the role they play in the production process;

For the purpose of this article we will use the classification of Sari [4]. Furthermore we restrict the possible production situations to complex, assembled products. Sari makes a distinction between:

(1) *make-to-stock*: converts lower-level components and raw materials all the way to end-items in anticipation of customer orders;
(2) *assemble-to-order*: converts lower-level components and raw materials to a predetermined level of manufacture, and configures to customer order upon receipt of a customer order;
(3) *make-to-order*: obtains very few, perhaps no lower-level materials until after receipt of a customer order;

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(4) *engineer-to-order*: knows very little about what to order or manufacture until after receipt of a customer order and development of engineering specifications.

The Manufacturing Resources Planning (MRP II) production control concept has especially been developed for the "make-to-stock" and (in specific situations) for the "assemble-to-order" situation (see Ref. [5,6]. MRP II focused on:

- batch production of well-known discrete standard products;
- products, consisting of many (different) parts and subassemblies;

The "make-to-stock" and the "assemble-to-order" situation differ from the "make-to-order" and "engineer-to-order" situation with regard to the role of the customer order in the production system. In the latter two situations the customer order plays a central role in the production system and the production control system. All production activities are customer order driven. Furthermore, in an "engineer-to-order situation", engineering and design activities are part of the customer order lead time. This means that non-physical activities too are subject to production control. Products are custom-made and one-of-a-kind. The production control characteristics of the "make-to-order" and in particular the "engineer-to-order" situation are thus different from the "assemble-to-order" and "make-to-stock" situation. As we will show this means that the production control concept underlying MRP II cannot be used in these production situations. However, many engineer-to-order firms have tried to implement the MRP II concept, without success.

In the first part of this article we shall discuss in further detail the deficiencies of MRP II in an engineer-to-order production situation. In Section 2 we will first describe the engineer-to-order characteristics. In Section 3 we will discuss the specific control characteristics. In Section 4 we discuss the deficiencies of using a standard MRP II system. In the second part of this article we will present a production control framework, which better suits the specific characteristics of the engineer-to-order production situation. This control framework has been designed based upon four production design principles which are described further in Section 5. The design of the production control framework, using these principles, is then covered in Sections 6 through 8.

2. The engineer-to-order production situation

Many industrial firms can be characterized as engineer-to-order. However, these firms may still differ in terms of:

- the complexity of the products;
- the degree of customer specificity of the product;
- the lay-out and complexity of the production process;
- the characteristics of the market and the competitors.

There is, for example, a great difference between a firm which manufactures customer-specific cardboard window displays, and a firm which manufactures complex customer specific industrial equipment. The production control framework presented in part II of this article is intended for every engineer-to-order production firm. However, in detail, the specific character and complexity of the control structure depends heavily upon the characteristics of the specific production situation. We shall take one specific engineer-to-order situation to elaborate the production control framework. The situation chosen can be considered a highly complex one. For an extended description of a similar engineer-to-order situation see Ref. [2]. The production situation will be described by the following characteristics:

- product characteristics;
- market and competitors;
- the production organization;

In this article we shall refer to this production situation as "the engineer-to-order situation".

2.1. Product characteristics

The production situation considered here produces and delivers complex machines. All machines are more or less customer-specific. The firm realizes about 50 to 60 customer orders each year. Each customer order consists of one or more machines to be delivered to one customer. Each customer order is preceded by a quotation. Only about 15% of the quotations leads to an order. Each quotation however requires a considerable amount of engineering capacity. The firm has invested a lot in product design independent of customer orders. The customer can, however, have a lot of influence on the product design through customer-specific requirements.

2.2. Market and competitors

The products are capital goods which are delivered to industrial firms. Sales are very sensitive to macro-economic fluctuations. This means that sales can vary from year to year. It is impossible to make a detailed sales forecast because the products are partly customer-specific and one-of-a-kind. There are many competitors which compete with both price and quality.

2.3. The production organization

Each customer order can be considered as a project with a network of partly overlapping activities, like engineering and design, component manufacturing, assembly and installation. The firm only realizes a few large orders a year (multi project organization). The manufacturing organization has a functional character with universal production machines. This is necessary, given the customer specific character of the products and the wide range of necessary production operations. Persons within the functional organization can be involved in many projects.

The goods flow to be controlled consists of two different major stages, namely a non-physical stage and a physical stage. The non-physical stage concerns the engineering and design activities (including quotation preparation) and the process planning activities. The physical stage concerns the component manufacturing, assembly and installation of the machines (see Fig. 1). The assembly know-how is of strategic importance and is never subcontracted. The internal component manufacturing capacity is limited because of the volume fluctuations in demand. During busy periods, capacity flexibility is found through subcontracting of component manufacturing.

3. Engineer-to-order control characteristics

The typical control characteristics of the engineer-to-order production situation can be

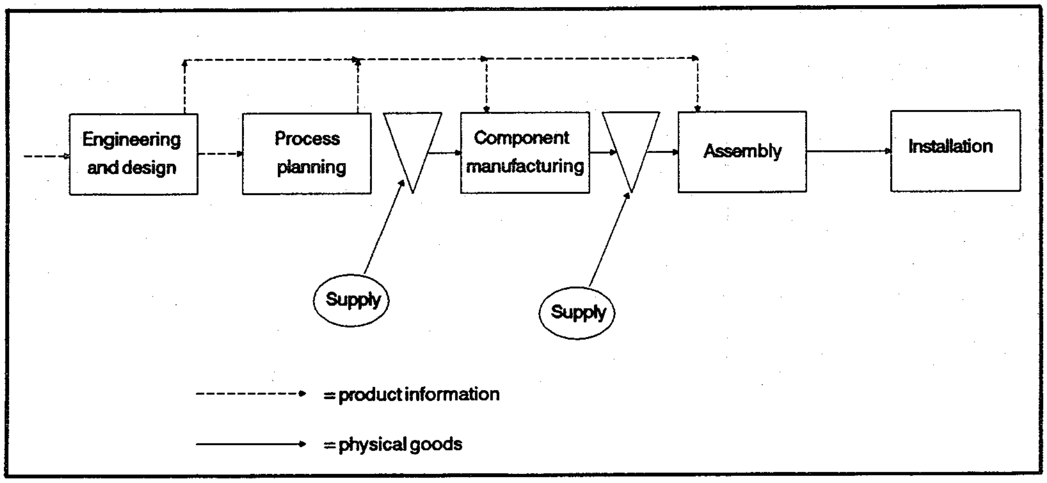

Fig. 1. Global goods flow.

described using the following three aspects: dynamics, uncertainty and complexity.

3.1. Dynamics

A production situation is called dynamic if one has to anticipate considerable fluctuations in, for example, sales volume. These fluctuations can be predictable but difficult to anticipate. The engineer-to-order firm has to cope with strong fluctuations in mix and sales volume in the short and medium term. This is a general characteristic (see Ref. [7]). Because of the customer order driven production, it is impossible to cope with these fluctuations by means of, for example, creating capacity stock [8]. This dynamic market situation asks for a lot of external flexibility to cope with these fluctuations.

3.2. Uncertainty

According to Galbraith [9] uncertainty is the difference between the amount of information required to perform a task and the amount of information already available in the organization. In terms of Galbraith, three uncertainty-factors can be distinguished, within the engineer-to-order situation. These factors have great influence on the complexity of the production control situation.

The first factor concerns the uncertainty of product specifications. Especially at the start of a project (non-physical stage of the goods flow), parts of the product are unknown. This implies a high level of uncertainty. Decisions concerning capacity, lead time and price have to be taken under uncertainty. During engineering, design and process planning activities, the work content and material content of a project becomes gradually known. More and more detailed product information comes available. Moreover, the design process itself is an uncertain process. For instance, it may be that the engineering and design activities of a specific project have cost twice as much capacity, as was estimated during quotation preparation. This might have serious project lead time consequences. A production control system should anticipate upon this type of uncertainty, regarding the design phase. Evaluation of former decisions and anticipation on new situations, as soon as detailed information becomes available, should be an important characteristic of the production control system.

The second factor concerns the mix and volume uncertainty of the future demand. Making a detailed demand forecast is very difficult because of the customer specific character of the product and the many different product lines. Especially with investment goods, sales demand could strongly fluctuate in time. An important extra uncertainty element is the moment of customer order intake. Because of the considerable competition and the relative low opportunity to score a quotation, always many more quotations are made than customer orders are received. The firm generally doesn't know if and when a customer places an order. This makes planning and reservation of capacity and production planning very difficult.

The third factor of uncertainty concerns the process uncertainty. Because the product is customer specific, parts of the machine are unknown at the beginning of the project. At that moment it is difficult to make an estimation of the type and amount of resource that will be required. In particular the specific type of the required resource is uncertain. In practice it appears that there are many different resource types required for many different product operations in the component manufacturing. As a result of this variation, the total amount of required and available production capacity could be in balance, while for individual operations it is completely unbalanced. A considerable external flexibility in the short term is required, given the occurring unbalance in required and available capacity.

3.3. Complexity

The production control situation can be characterised as complex because of three main factors.

The first factor is the structure of the goods flow. The goods flow to be controlled not only consists of a physical stage but of a non-physical stage as well. The non-physical stage concerns the engineering and design and process planning activities. The physical stage concerns the component manufacturing, assembly and installation of the machines (see Fig. 1). Given the partly creative design processes in the non-physical stage, the work is difficult to formalize. It is difficult to distinguish production phases and operations in analogy with the physical production. This means that it is difficult to determine the progress of a certain piece of work, for example, within the engineering department.

Moreover, the engineering department has to take into account the capacity that is required for quotation preparation. Generally, a relative high fraction of the available manhours in design and engineering is used for quotation preparation. This may interfere with the amount of capacity required for realizing the already placed customer orders. This conflict between short term objectives (realizing placed orders) and longer term objectives (acquiring new orders) is specific for this kind of situation.

The physical stage is complex too. The component manufacturing and the assembly departments have a complex internal structure. The component manufacturing department can be characterized as a job shop. This means complex capacity coordination with many different product routings and varying operation times. The assembly departments can be characterized as dock production. Assembly operations take place at certain specially equipped assembly locations. The locations are more or less machine type specific. These locations form one of the difficulties in planning the assembly activities. Given the complex construction of a machine with thousands of parts, both the capacity and material coordination within the assembly locations are complex.

The second complicating factor is the multi-project character of the situation. Every customer order consists of a network of activities of which parts maybe unknown at the initial stage of the project. Within the same departments, there are various projects to be controlled at the same time, in different stages of completion. Bottlenecks that occur as a result of the existing uncertainty within one projects can have serious effects on the other projects on hand. In this situation the correct planning and coordination of all projects and project activities is a complex matter.

The third complicating factor is the composite or assembly structure of the product. It may consist of thousands of spare parts that are partly customer specific and basically one-of-a-kind. This means that specific materials may have to be specially purchased for a specific project. This could mean that some specific materials have to be purchased in an early stage of the project as a result of long lead times, without knowing the full details of the product structure.

An effective production control structure for the engineer-to-order situation has to reflect all of these specific control characteristics.

4. MRP II in an engineer-to-order situation

During the last decade many engineer-to-order firms have tried to implement MRP II systems, however, with little or no success. The choice of a MRP II system is often based on the wide availability of MRP II software and the fact that the exact reasons why this software is not suitable for engineer-to-order firms are not understood. Therefore, the many implementation failures are not surprising. First we shall describe the characteristics of a standard MRP II system. Subsequently we shall contrast these characteristics with those of the engineer-to-order situation. With this we will demonstrate the non-applicability of the MRP II system in an engineer-to-order situation.

4.1. Characteristics MRP II system

The essence of the MRP II approach to production control can best be described as follows (see Refs. [5,6]):

- determine for final products or the equivalent of final products what should be produced at what time (called the Master Production Schedule: MPS), taking into account the capacity consequences;
- calculate the required production of subassemblies, components and materials, based upon an up-to-date Bill-Of-Materials (BOM), the available inventories and work-in-process, the batch sizes and the manufacturing and purchasing lead times.

From these characteristics and this calculation logic we can derive the basic assumptions of the use of a standard MRP II system. It assumes the production of standard products with a well-known BOM and product routing. To use a MRP II system, all detailed information about products and production process have to be known in advance. The MRP II logic thus assumes the availability of all required information. In terms of Galbraith [9], MRP assumes the absence of any form of uncertainty. MRP II is in fact a deterministic production control system. In fact, it cannot cope with any form of uncertainty (see Ref. [10] for an extensive description of MRP and uncertainty). Furthermore it assumes that it is possible to forecast the future demand of the standard products as a basis of the MPS. Because the MPS is mainly derived from the demand forecast, the production can be described as anonymous batch or mass production. There is no relationship with a customer order during production of the products.

4.2. *The non-applicability of MRP II*

When we contrast the control characteristics of the engineer-to-order situation with the basic assumption and characteristics of a standard MRP II system we can easily demonstrate the non-applicability of MRP II by the following elements:

- the use of the BOM;
- the relation between customer order and work orders;
- the control of non-physical processes;
- the extent of information detail;
- actual cost report of customer order.

In an engineer-to-order situation the product is customer specific and in the start of the project partly unknown. This means that the project-BOM comes gradually known during the project. Every product and project has its own specific BOM and a new project-BOM is created for every new project. A standard MRP II system cannot cope with the fact that the project-BOM is incomplete or only roughly known during the initial phase of the project. The MRP calculation logic assumes a complete and detailed product BOM.

Project-BOMs are (partly) constructed with the use of so called standard BOMs. Standard BOMs are earlier constructed product functions or product modules that have been generally accepted as product standards within the engineering and design department. In addition to standard BOMs, historic BOMs of previous projects are used during product construction. The distinction between standard, actual and historic BOMs is very important in the engineer-to-order situation and asks for specific information support. The connection between these types of BOMs is illustrated in Fig. 2. A standard MRP II system does not support the distinction between these type of BOMs. This means that the three types of BOMs have to be put in one large BOM-database, without any distinction. This leads

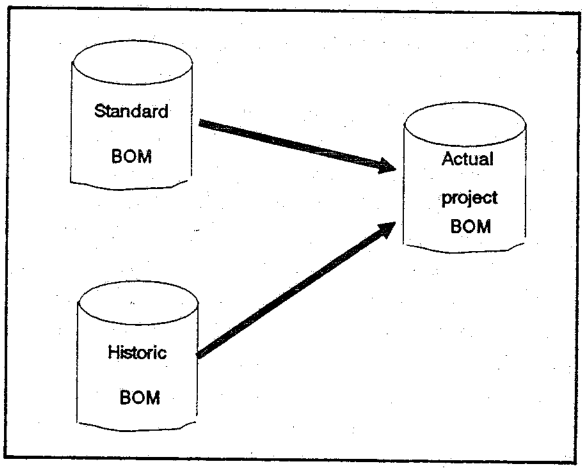

Fig. 2. Relationship between different BOM types.

easily to an immense and polluted database with a considerable chance of making mistakes.

In an engineer-to-order situation every product is customer specific and one-of-a-kind. It must be possible to follow the production progress of all activities and parts for the customer order in the goods flow. There has to be a relation between the customer order (the project) and all of the corresponding work orders within the various departments. This relation is impossible in a standard MRP II system. MRP II supports the production of standard products. A work order is anonymous and could be related to many different future customer orders. In a standard MRP II system work orders can only exist if they are to produce a certain amount of a standard product. This standard product should be defined anonymously, i.e. independent of a customer order, in the BOM-database. In engineer-to-order production, a work order may exist purely because there happens to be a customer order requiring the materials produced by this work order. The difference between the engineer-to-order situation and the MRP II system with respect to the relation between customer orders and work orders is illustrated in Fig. 3. The graphical notation for representing data structures is derived from Ref. [11]. To some readers, this difference may appear as a minor detail. Such an impression, however, is false. It is a considerable effort to change an information system based on MRP II into another information system, which allows for customer-order based material tracking (see for an extensive description, Ref. [2, ch. 6].

As is depicted in Fig. 1, parts of the goods flow in an engineer-to-order situation consist of non-physical activities like engineering and design. Because these activities are part of the project throughput time, they are subject to production control too. These activities produce "products", like product and production specifications. A standard MRP II system does not have any facilities to control these non-physical processes.

During the execution of a project both the work and material content of the product becomes known only gradually in an engineer-to-order situation. This means that only aggregate information is available for production

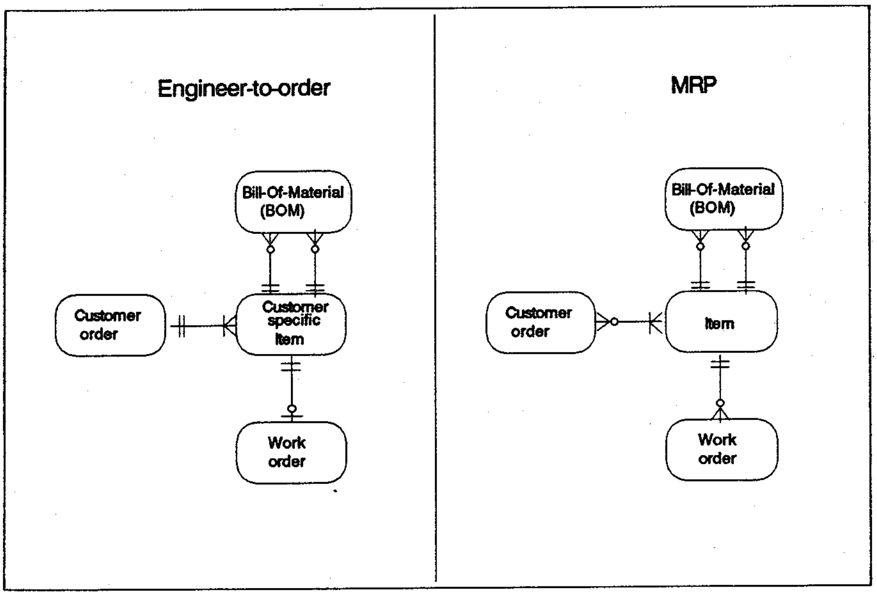

Fig. 3. Relationship between workorders and customer orders.

control at the start of a project. Each customer order is considered as a network of aggregate activities. During the non-physical stage of the goods flow, more detailed project information comes available. Aggregate activities are refined into more detailed activities, to be called workorders. The relationship between aggregate and detailed activities is illustrated in Fig. 4. A standard MRP II system cannot make the distinction between aggregate uncertain information and detailed information. This is the fact because it is focused on the production of standard products which are known in detail. Information support for production control "from aggregate to detail" is then not necessary. However, in MRP II one aggregate control level exist, i.e. the rough cut capacity check at the Master Production Scheduling. However, the procedures used, suggest that the aggregate bills of capacity, used to check the MPS, are designed for standard products.

Projects are customer specific and one-of-a-kind. This means that product prices are specific and are determined in negotiation with the individual customer. A cost budget is made for every project during the quotation stage as a basis for price-setting. After completion of a project it could be useful from the viewpoint of financial control to make an actual cost report of the project to contrast it with the cost budget. An important condition for an actual cost report of a project is the possibility to link production hours, used material, project purchases etc. to the related project. In a standard MRP II system this is impossible because there is no relation between individual work orders, purchase orders etc. and customer orders.

5. Production design principles

Bertrand et al. [2] have developed four general design principles for designing a production control framework for production environments. These design principles are:

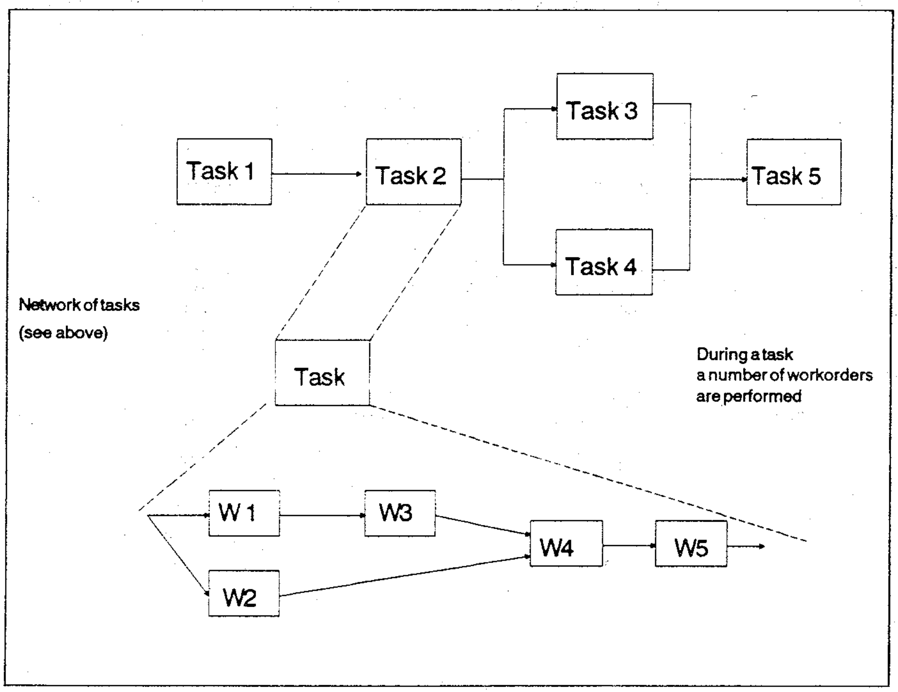

Fig. 4. Relationship between aggregate and detailed information [2].

- the decision structure should be seen as the basis for a production control framework;
- a distinction should be made between goods flow control and production unit control;
- a distinction should be made between the detailed item-oriented planning and control and the aggregate capacity-oriented planning and control;
- special attention needs to be paid to the interface between Production and Sales.

5.1. The decision structure is the basis

The design of a tailor-made set of feasible, organizational decision functions (see Refs. [12,13]) is essential for establishing a good control frame-work. With respect to structuring these decision functions, Meal [13] as well as Bertrand and Wortmann [12] recommend the use of a (organizational) hierarchical decomposition technique to divide the total production control problem into sub-problems with a (partial) hierarchical decision structure. The complexity of the production control problem is reduced by defining a number of sub-problems, each of which can be solved independently. The assumption is that it is virtually impossible for a central production control function within a given organization to work at both a global level and a detailed level. The top management level in an organization should not be involved in all of the decision at a detailed level; these decisions need to be delegated to hierarchically lower levels in the organization. This delegation of detailed decision-making authority must nevertheless be structured in such a way that the production control of the total process is still possible at the highest level of management in the organization. This can be achieved by decomposing the decision structure hierarchically into subproblems in such a way that aggregate decisions include a definition of the boundaries within which the detail decisions need to be taken (refer also to Ref. [14]). The sub-problems which are defined in this way can then be solved independently and delegated to hierarchically lower functional units in the organization (comparable to "autonomous groups" as described by Burbidge [15].

5.2. Goods flow control versus production unit control

The total production control problem consists of coordinating the materials and the resource capacities for the whole chain of production activities starting with the purchase of materials to the sale of finished goods. The production control activities are numerous and (often) complex. In view of the different nature and time-frames associated with these activities, it is not sensible to have only a single central function in the organization which is responsible for carrying out all of these production control tasks. The total production control problem can be simplified by defining an equivalent set of (organizational) sub-problems as indicated above. In connection with this, two hierarchical production control levels can be identified: the production unit control (PUC) level and the goods flow control (GFC) level. Goods flow control is concerned with the overall coordination for a chain of *production phases* (the logistic chain). Each production phase then becomes a set of operations with an input material or product which is transformed to an output material or product. Subsequently, the production phases are assigned to a so-called production unit (PU). A PU is an organizational grouping of resource capacities (refer also to the previous section) with the following characteristics [16]:

- internally organized such that the operations (associated with the assigned operations set) which are required to complete a given production phase can be performed independently, provided that the required materials and sources capacities are available;
- capable of making reliable commitments with respect to the specific conditions (such as utilization levels, throughput times, etc.) under which the operations belonging to a given production phase for a specified volume and for specified periods of time can be performed.

In this way the production control problem is solved at two levels: the production unit control (PUC) level and the goods flow control (GFC) level. The use of GFC provides only for the coordination of the production phases in the primary process. At this production control level the total primary process is defined only in terms of a set of production phases with relationships between these phases. Each production phase results in the delivery of a specified (intermediate) product which is referred to as a *GFC item*. Coordination of the production phases at the GFC level is accomplished by releasing work orders to the PUs to carrying out specific production phases to produce GFC items. A work order is therefore an instruction to initiate and complete a specific production phase. Each individual PU is responsible for completing all of the work orders assigned to it in accordance with the established agreements. It should be obvious that the goods flow control cannot release work orders for processing by a PU without taking into account various factors such as the availability of resource capacity and materials. This release decision is based on aggregated data at a higher level, however. An important design aspect in this connection is the identification of the different PUs and the design of the logistic chain. The autonomy of the individual PUs and the importance of PUC both increase when there are fewer PUs in the logistic chain.

5.3. Aggregate Production Planning versus Operational Production Planning

The following two production control aspects can be identified with respect to the coordination of PUs at the goods flow control level, each with its own production control horizon:

- the coordination and matching at an aggregate level. This involves matching the available resource capacity to the capacity requirements. This is a medium/long term coordination activity primary based upon aggregate data. This is because short-term adjustments to the resource capacities are generally not possible and because information about the required capacity (especially in engineer-to-order situations) can be extremely unreliable. We will refer to this production control aspect as *Aggregate Production Planning* (APP);
- the coordination and matching at the detail level. This involves the timing of work orders or, in other words, the periodic assignment of available resource capacity to individual products. This can be seen as the short-term coordination of specific products primarily based upon detailed information. We will refer to this production control aspect as *Operational Production Planning* (OPP). The two major components of OPP are Utilization Planning (capacity aspect) and Material coordination (material aspect). These two levels of goods flow control are represented in Fig. 5.

5.4. Interface between Production and Sales

The objective of goods flow control could be formulated as coordinating the interface between Sales and Production, taking the resource capacity and the timeliness of product delivery into account. Sales is responsible for ensuring sufficient product demand and for accepting customer orders. Production is responsible for providing production capacity and ensuring that the customer order is completed on schedule. At certain points in time, however, both Production and Sales will be confronted with limitations and requests which conflict with each other. These situations occur periodically when there is an imbalance between the required and the available resource capacity due to a certain amount of inflexibility in the production capacity, the current workload levels and the available stock. For this reason it is important that the interface between Production and Sales is included within the scope of the control framework.

Using these design principles, a production control framework will be developed and described in the subsequent sections. This control framework will be designed specifically for a particular engineer-to-order situation as

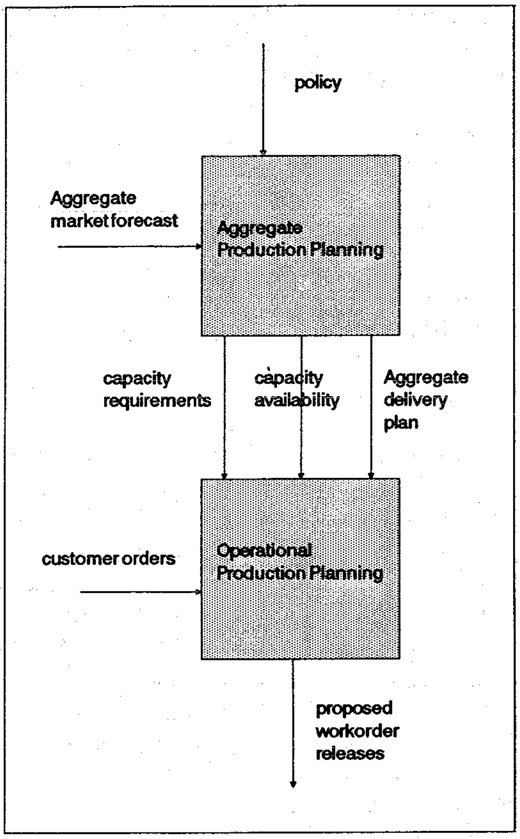

Fig. 5. Components of the goods flow control.

described in section 2 and will be developed here in three steps. The logistic chain is designed as the first step (Section 6). In connection with this, a distinction is made between Production Unit Control and Goods Flow Control. The various production control functions are then developed as the second step (Section 7). Special attention is paid to the distinction between Aggregate Production Planning and Operational Production Planning and the interface between Sales and Production. The third and final step is to develop the decision structure within this control framework (Section 8).

6. The logistic chain for the engineer-to-order situation

The term "logistic chain" is used here to refer to the part of the primary process which is subject to production planning control. Designing the logistic chain simply means the sensible arrangement and structuring of this part of the primary process from a production point-of-view. A general description of the primary process typically found in an engineer-to-order plant was presented in Section 2. We will now describe how this primary process can be structured from an production perspective, based upon a number of design principles.

Three design principles can be identified for structuring the primary process for the purpose of production planning and control (refer also to Ref. [2]). This primary process involves a specific set of production steps which are needed to manufacture a finished product. Using these principles, a number of steps can be identified to design the logistic chain for an engineer-to-order situation. These steps are:

- defining the operations;
- identifying the GFC items and production phases;
- establishing the production units.

Structuring the logistic chain in this way is still dependent to a large extent upon the specific situation because the decision criteria are partially dependent upon the specific products produced by a plant and the manufacturing technology used. In generic terms, however, a logistic chain can be designed based upon the typical characteristics of an engineer-to-order manufacturing situation in which (complex) discrete products such as industrial production machinery is manufactured and assembled. We will refer to this as the generic logistic chain. It is primarily the definition of the operations which will be dependent upon the particular situation. Therefore, there are few generic statements to be made with respect to the definition of operations. The relationships between the definition of operations and the primary processes are discussed in more detail by Bertrand et al. [2]. Here we will concentrate more on the identification of generic GFC items/production phases and the establishment of generic production units based upon the typical engineer-to-order situations. In addition, we will point out where a specific situation may differ from the generic situation with respect to the logistic chain. The last part of this article will focus on the production control framework associated with the generic logistic chain.

6.1. Identifying the generic GFC items and production phases

The production control issues can be divided into GFC issues and PUC issues through the creation of production phases and GFC items. Five generic production phases and related GFC items can be identified by applying the previously-mentioned criteria.

The first generic production phase is the development of a global (functional) conceptual product design (= the GFC item for this phase) during the tender stage. In general, it is necessary to develop the specifications for the conceptual product design for a specific customer to a given level of detail, to ensure that a tender can be provided which includes a specified price quotation and delivery date which can be realized within acceptable margins of risk. Upon completion of this phase, an important part of the (product) uncertainty will have been eliminated; it will be important to report this information at the GFC level. It is assumed that it is not worthwhile to work out all of the details of the conceptual product design during the tender stage since the probability of tender acceptance and the likelihood of being able to continue with processing in the next phase is relatively low in this business.

The second generic production phase is the preparation of a detailed (functional) conceptual product design (= the GFC item for this phase). It is assumed that this phase will be initiated after a tender is accepted and becomes an approved order. This production phase results in a detailed view of the (functional) design of the product, providing a better estimate of the amount of engineering capacity required to complete the product design. The uncertainty is thus also reduced significantly at this point. It may also be necessary to assign priorities to orders at this point in the event that bottlenecks exist with respect to the availability of the engineering capacity.

The third generic production phase is the completion of the detailed product specifications in the form of engineering drawings and bills of materials (= the GFC item for this phase). After this production phase it is known which components and assemblies will be needed to manufacture the product and it will be possible to determine which production resource capacities will be required. The product uncertainty is reduced to zero at this point. The updated information in this connection is required at the GFC level.

The fourth generic production phase is concerned with the manufacturing of the components and basic assemblies (= the GFC items for this phase) which are required for the final assembly of the product in the next phase. Activities which precede the physical manufacturing stage such as preparing the production documentation (process planning) for the various components and ordering the necessary materials and tooling are also included in this production phase. Separate work orders are issued for the manufacture of the various components due to the (assembly) structure of the product. It can be assumed that not all of the components will be required at the same time for the assembly activity. Therefore, it will be necessary to issue separate work orders for the manufacture of individual components to ensure that certain components will not arrive too early at the assembly location. It will be desirable to report updated information at the GFC level at this point to allow for a proper coordination of the component manufacturing and assembly activities.

The fifth and last generic production phase is the assembly of the finished product (= the GFC item for this phase) from the various components. The assembly planning and the preparation of assembly instructions, of course, precede the physical assembly process.

6.2. Establishing the generic production units

Four generic production units are needed based upon the generic production phases defined above and the criteria for establishing such production units. The production phases of "developing a global conceptual product design" and "preparing the detailed conceptual product design" can be processed within a single production unit. The nature of the required capabilities is the same for both of these production phases and the activities will generally be carried out by the same person or persons. We will refer to this production unit as "Conceptual Design". The production phase of "completing engineering drawings and bills of materials" can be processed within a single production unit. The nature of the required capabilities is significantly different from the required capabilities in the previous and subsequent production phases; the human resources cannot be shared. We will refer to this production unit as "Product Engineering". The production phases of "manufacturing components" and "assembly of the finished product" are each assigned to a separate production unit. The production control issues and the nature of the required capabilities and resource capacities for manufacturing components is clearly different from the requirements for final assembly. The generic production units will be referred to, respectively, as "Component Manufacturing" and "Assembly".

The logistic chain for a specific situation will generally be different from the generic chain described here. For example, if a plant produces more than one family of products which are completely different in terms of the use of technology, then various parallel and independent production units may be found in each part of the logistic chain. In practical situations, more than one production unit may be required for Component Manufacturing and for Assembly, depending upon the extent of the production facilities and the available capacities. When the activities for process planning, materials requisition and making arrangements for special tooling are added to a single PU for Component Manufacturing, this means that this PU must have complete, autonomous control over all of these types of activities. At the GFC level it is assumed that the PU for Component Manufacturing will be directly responsible for performing these activities as part of the work order processing. Having separate PUs for Process Planning, Materials Requisition and Component Manufacturing could very well be a viable alternative in certain instances. Nevertheless, the generic logistic chain as diagrammed will be used as the reference model in this article for developing a production control framework for an engineer-to-order manufacturing situation.

7. Developing the production control framework

Two levels for production control can be identified within the production control framework based upon the general design principles presented in Section 5: Production Unit Control (PUC) and Goods Flow Control (GFC). The logistic chain contains both physical and non-physical processing stages and consists of four PUs in total. A local production control function can be defined for each of these PUs. GFC provides for coordination during the non-physical as well as the physical stages of processing in the logistic chain. At this point it is useful to investigate the characteristics of GFC in more detail. Three production control aspects can be identified within the GFC (refer also to Section 5):

- Aggregate Production Planning (APP);
- Operational Production Planning (OPP);
- the interface between Production and Sales.

7.1. Aggregate Production Planning (APP)

An Aggregate Production Planning (APP) activity is included within GFC, which is independent of the operational control of customer orders. This concerns the medium-term matching of required resource capacity with the available capacity. The available capacity is adjusted as much as possible to be able to meet the estimated future capacity requirements through the use of, for example:

- arrangements with external suppliers for outsourcing capacity;
- fewer or extra work shifts;
- temporary employees to provide additional assembly capacity, etc.

The APP, in particular represents an important production control function in engineer-to-order manufacturing situations. These types of products are generally capital goods for which the demand may vary widely depending upon the economic climate. This means that the demand for production capacity can be radically different from one period to the next. It is important to be able to anticipate such changes as early as possible.

7.2. Operational Production Planning (OPP)

In addition to APP, the operational coordination of the processing of the production phases of the customer orders is covered by GFC. This production control aspect is also referred to as Operational Production Planning (OPP). This involves the coordination of materials as well as the capacity scheduling for the flow of goods. The available resource capacity is assigned to customer orders and work orders at this point. The characteristics of OPP are different in the different parts of the logistic chain. Specifically, the production control of the customer orders at the start of the logistic chain (i.e. during the non-physical processing stage) is carried out based upon aggregate data. This is due to the relatively large amount of uncertainty at this point and the lack of detailed information about the product to be manufactured. The OPP function focuses primarily on the resource capacity aspect at this stage. The material aspect here is limited to the acquisition of the critical materials and components with a long delivery lead time. During the tender stage, a global network plan is prepared for each potential customer order. This network plan consists of aggregate activities and milestones which are used at the basis for capacity planning and estimating throughput times. As more product information becomes available during the non-physical stage, the global network plan is modified and details are added. This global network plan is also used to monitor the progress of each individual customer order. The production control activities are similarly performed at a more detailed level and the material aspect receives more attention with the scope of the OPP activities when additional product information becomes available. This essentially concerns the coordination of materials and the determination of relative priorities for the work orders in the PUs during the physical processing stage. All of the product details are known by the time that the process planning has been completed for a customer order. A detailed planning is prepared for the various work orders associated with a given customer order, based upon the global network plan with the aggregated activities. The work orders are then released in collaboration with the heads of the various PUs.

Even after the detailed information about a customer order is known, it is still convenient to track the progress of a customer order during the physical processing stage using the customer order network. The aggregated data used in this network provides a good basis for tracking the progress of each customer order.

7.3. The interface between Production and Sales

In view of the fact that the customer orders arrive at the start of the logistic chain and that the degree of uncertainty is the highest at this stage, the most important production control decisions are taken at the GFC level. The operational arrangements between Sales and Production, in particular, are important at this stage and are included as an explicit part of GFC. This is especially true in engineer-to-order situations. An open and intensive exchange of communications between Sales and Production is especially important during the tender phase (refer also to Ref. [7]). A global product design specification is prepared based upon specific customer requirements. This is then used as the basis for calculating the price and delivery schedule for inclusion in the quotation. The capacity requirements at each work station are still quite indefinite at this stage, however, since the products to be manufactured are more-or-less unique and customer-dependent. Conditions and circumstances may change during the customer order negotiation phase, for example:

- the customer may change his original specifications, with significant implications for the required resource capacities;
- a number of other customer orders may have been accepted while the negotiations were taking place, reducing the availability of future resource capacity;
- the capacity requirements of previously accepted orders appear to be greater than originally anticipated. This reduces the amount of capacity which is available for new orders;
- the order negotiations extend over an extremely long period of time, leading to changes in the original estimates of the total capacity requirements.

Each of these situations can have an effect on the delivery date to be specified in a tender. A continuous revision and reconfirmation of the relevant conditions between Sales and Production is therefore essential. The point in time at which the customer order is actually placed is also an important factor in coordinating efforts in this area. Due to the competitive nature of the engineer-to-order manufacturing business, any tender for new work will generally have a relatively low probability of being accepted. A potential customer normally asks for several tenders from different suppliers in view of the large size of the investment and the type of product (typically industrial machinery). This means that a potential customer may not decide to place an actual order. If he does, however, it is usually not clear when the order will be placed. A long period of time may elapse between submitting the tender and placement of the corresponding order. Nevertheless, by keeping in touch with the potential customer, Sales is often able to provide a reliable estimate of when a tender is likely to result in the placement of an order. Production needs to be aware of this so that orders do not arrive unexpectedly with commitments for delivery which can no longer be realized.

8. Developing the decision structure

Up to this point we have been able to identify the major functions with respect to production control. A distinction has been made between an integral Goods Flow Control (global planning) and local planning and control at the PU level. More substance can be given to the various production control functions by developing a decision structure. The decision structure which is applicable to an engineer-to-order manufacturing situation is comprised of the following four key production control decisions at the GFC and PUC levels:

1. Customer order acceptance and due date assignment (GFC); is a timely completion of the production of the customer order possible?
2. Sub-order assignment and PU outsourcing (GFC); which production unit will be manufacturing which components and what part of the work will need to be contracted out (outsourced)?
3. Work order release (PUC); when will the work be released to the production unit?
4. Work sequencing (PUC); in which sequence will the work be performed within the production unit?

These four key production control decisions are discussed in more detail in the following subsections.

8.1. Customer order acceptance and due date assignment

Control over the throughput times within the individual production units is a necessary but not a sufficient condition for being able to control the throughput time of the whole customer order. This is because the throughput times within a PU are only controlled at the PUC level. The integral coordination between Sales and Production should take place at the GFC level (refer to the previous section). The most important decision in this respect is the internal order acceptance and the due date assignment. A major part of the production organization is, in fact, driven by this decision. This includes deciding how much effort is to be spent preparing a tender in each specific case, what delivery lead time will be quoted and what the price will be. A good structural and operational interface between Sales and Production is needed in view of the prevailing uncertainties.

If we visualize the order acceptance and due date assignment decision as being a regulating valve, then the quantity of work flowing into the production organization can be controlled by opening and closing this valve. In practice, a major part of the production and financial control problems within engineer-to-order manufacturing plants could be solved by implementing an effective valve to regulate the work flow in this way. It is apparent that this key decision deserves more attention than it currently receives in the literature as well as in practice (see also Ref. [7]). A large number of variables and other factors need to be taken into consideration in making this decision. These factors include the future capacity loading, the relative value of a potential order, the desired delivery lead time, the probability of a tender becoming a firm order and the technical risks. Various business disciplines such as Sales, Engineering and Production/Productions are involved in the order acceptance and due date assignment decision. Sales is responsible for determining which price will be quoted in the tender and also plays an important part in compiling all of the customer specifications. Engineering (or Product Development) is responsible for translating the customer specifications into the technical specifications for a manufacturable product. Engineering must also provide an estimate of the technical risks associated with accepting all of the customer's wishes when the order is accepted and the due date is assigned. For this purpose a high-level conceptual product design needs to be prepared, the capacity requirements need to be estimated and the risks must be evaluated. This is then used by Sales to determine the quotation price and by Production to determine the delivery lead time. This decision is taken at the GFC level since it can be characterized as being an integral decision.

8.2. Sub-order assignment and outsourcing

The first key decision is typically taken when there is still a great deal of uncertainty. Usually only a part of the manufacturing characteristics of a custom-made product will be known at the point in time when such a customer order is accepted and the due date is assigned. Nevertheless, a delivery lead time and a price have already been set. A major part of this product uncertainty disappears when the custom-made product is fully developed within the Conceptual Design and Product Engineering PUs. A much better estimate of the required quantities and types of resource capacities can be made at this point. Even before the process planning takes place, it is possible to assign the manufacturing of components to a specific PU (assuming that there are two or more PUs for component manufacturing and/or assembly activities) based upon the technical content of the work. The customer order is split into so-called *sub-orders* for this purpose. A sub-order is defined as being the collection of all of the work associated with a single customer order which is to be processed during a given period of time in a given PU. Each sub-order is assigned to a specific PU before the capacity loading is analyzed. If one or more of the PUs have insufficient capacity, then a number of the sub-orders could be sourced out to an external supplier.

In Section 2 it was explained how flexibility with respect to the volume of products in a component manufacturing situation can be realized by outsourcing some of the work to suppliers. In view of the availability of volume flexibility in this way, the second key decision has the following two objectives:

- Assigning the sub-orders to PUs as quickly as possible to enable an evaluation of the capacity loading situation within the PUs as soon as possible. This evaluation can then be used to determine which sub-orders are to be processed internally and which sub-orders, if any, are to be contracted out. When sub-orders are assigned at an early stage in this way, the PU department heads are then able to evaluate the future demand for their resource capacity and take timely action as appropriate.

- Review of the first key decision in the light of new information which has reduced the level of product uncertainty. Corrective measures will need to be taken in connection with the second key decision if it appears that certain variables have developed in a way which is contrary to the original expectations. Examples of corrective measures are, for example, the use of available slack time, extra outsourcing and the use of internal flexibility.

In view of the fact that delivery lead times for outsourcing tend to be longer than the internal production throughput times, it is extremely important to make arrangements for out-sourcing as early as possible. A plant can be more flexible and react quicker to changes in the market when it is able to arrange for outsourcing more quickly than its competitors. Delivery problems typically occur in practice when the work to be contracted out is not released at an early date.

The concept of *sub-orders* as used in this article is of primary importance for the control framework presented here because this provides the most important link between the non-physical and physical processing stages in the logistic chain. The use of sub-orders also implicitly provides a vehicle for communicating product information to the component manufacturing unit. All of the component drawings for a given sub-order are first completed within the Engineering PU before the complete sub-order is transferred to the PU where the components are to be manufactured. The sequencing of operations within the Engineering PU occurs at the sub-order level (with priority being given to the sub-orders on the critical path in the customer order network). Agreement is achieved between the GFC and the PUC concerning the internal due dates for the sub-orders. The PUC of the components manufacturing unit controls its own process planning, materials requisition and manufacturing for the various components included in each sub-order.

8.3. Work order release

The decision structure should be designed to allow for controlling the throughput time of the customer order as much as possible and also for ensuring that the targeted capacity utilization levels can be realized. The throughput time of the customer order is determined by the throughput time of the activities within the various production units which are on the critical path of the customer order. The objective of PUC is to accept work orders and to ensure the realization of the accepted work orders within the agreed throughput time, taking the agreements regarding utilization levels, throughput times and batch sizes into account. A significant amount of research has been done on controlling throughput times within production units; refer, for example, to Refs. [12,17,18]. These studies have demonstrated that throughput times are dependent upon, among other factors, the workload level found within the production unit. The more work found on the shop floor, the longer the average throughput time will be for newly accepted work orders. Throughput times can therefore be controlled by controlling the workload level. This can be accomplished by controlling the release of work to the production unit (see Refs. [7,12]). This type of controlled release of work to a PU differs radically from the method of *input/output control* described in the literature. Input/output control focuses on controlling the wait-queue at each *work station* as opposed to each PU. Control per work station means that GFC will directly influence the sequencing of operations on the shop floor. This approach is therefore not consistent with the principle of having autonomous PUs.

The controlled release of work orders to a PU has the additional organizational advantage the capacity problems can be recognized at the earliest possible point in time.

If, for example, equipment failure or operator illness results in an increased workload within a PU, then the planned quantity of work cannot be released. This would be noticed immediately. This means that GFC can be used to determine the consequences of the backlog so that corrective measures can be taken. In a situation where the work would be released to the PU, regardless of the backlog, the consequences would not be noticed until a much later point in time when corrective measures would be less effective. The third key decision of releasing work to a PU is the first control decision at the PUC level. This type of decision about releasing work is, of course, applicable to the PUs in the physical processing stages as well as to the PUs in the non-physical processing stages.

8.4. *Work sequencing*

An additional (combined) control decision is taken within the production unit which influences the throughput time performance of the PU after the work is released to the production unit. Within each PU there is a certain amount of work present (the workload) which has been completed to various degrees. Each day it is necessary to determine which resources have to be allocated to which work and in which sequence the work will be completed.

In other words, the sequencing of processing the work orders within the production unit must be determined. A multitude of details and condition are taken into account and anticipated at this stage which could not be included in earlier versions of the plans, such as: combining similar types of work, utilizing alternative equipment and machinery, reallocating human resources from other work stations. A certain amount of flexibility is required on the shop floor to allow for an adequate coordination of the various work orders in view of the uncertainties and the stochastic nature of this type of manufacturing environment.

The fourth key decision, the sequencing decision, is the second decision at the PUC level. The positioning of the four key decisions in the production control diagram at both control levels is illustrated in Fig. 6. An extensive analysis of the third and fourth key decisions has been published by Bertrand and Wortmann [12].

8.5. *Discussion*

Contrary to other production approaches, the decision structure is seen here as an explicit part of the control framework. The requirements which follow from the specific control characteristics of an engineer-to-order situation can be anticipated through the coordinated use of the four key production decisions described here. By taking these decisions in the specified sequence as a customer order is being processed, the various customer orders can be controlled in a top-down (global to detailed) manner. The production decision structure described here is also based upon a clear organizational concept. Each decision is associated with a specific organizational entity with the associated responsibilities and authorizations. The delegation of production control responsibilities to the shop floor, to the greatest extent possible, is of utmost importance in an engineer-to-order situation with its specific characteristics (uncertainties, etc.). As one gets closer to the actual production processes, one gains a better feeling for the changes which are occurring, enabling a quicker and more effective response. This means that the creation of a central control organization in which all of the production control decisions are concentrated would be counter-productive. Nevertheless, there is always some basic requirement for central coordination.

The delegation of decision-making responsibilities is explicitly included in the decision structure described here. The first key decision is generally taken collectively by the commercial management and the production management or, occasionally, by the complete management team. The second key decision is taken by the productions manager together with the heads of the production departments. A meeting is held with the heads of the production departments at the earliest possible

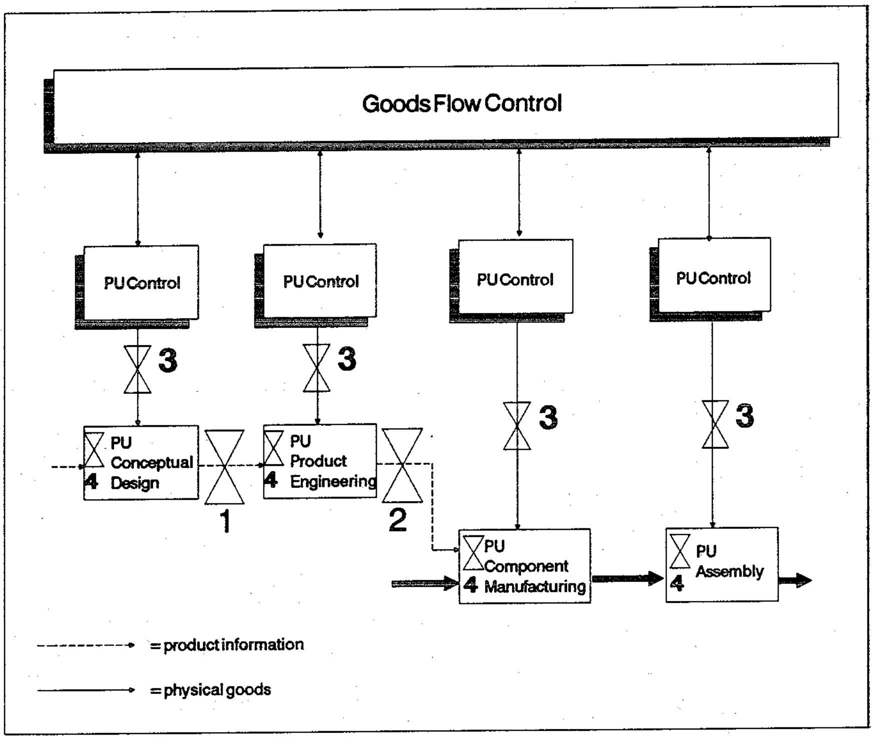

Fig. 6. Position of the four key decisions in the production control diagram.

moment to discuss the implications of the quantity of work which is expected. In this way they are given adequate time to take any measures which may be appropriate. The third key decision is taken by each head of a production department together with the group leaders within his department. Finally, the fourth key decision is taken by each group leader together with the individual workers in his group. As the order progresses along the logistic chain, the responsibility for making control decision becomes increasingly closer to the operations on the shop floor. The requisite authorities for taking these decisions must, of course, also be established.

9. Conclusion

In the first part of this article we have contrasted the characteristics of the engineer-to-order situation with the characteristics of a standard MRP II system. Our conclusion is that a standard MRP II system is not suited for the engineer-to-order production situation. In the second part of this article a framework has been presented for production control in engineer-to-order manufacturing plants. The description of this control framework is based upon the design of a logistic chain, the distinction of different levels of control and the identification of four key production decisions. The production control framework described in this article has already been implemented successfully in a number of practical situations involving various engineer-to-order manufacturing plants. It has been proven to be a valuable instrument in all of these instances. Since each individual production environment has its own special characteristics, the control framework must be adapted to take these characteristics into account as necessary at the detailed levels. The control framework presented here is also applicable to situations in which an order for custom-made production may be less complex. In a simplified situation the production control decisions and functions will be less complicated but the basic structure of the framework will remain the same.

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