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Production management systems for one-of-a-kind products

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The term “one-of-a-kind production” covers a diversity of industries. Therefore, this paper presents first of all a typology of one-of-a-kind production systems. The typology is based on two questions: Which part of the supply chain is customer-order driven? What investments in resources, products or processes have been made independently of customer orders? Next, the paper investigates key areas of management attention for several types in the typology with a focus on production management problems. These production management problems are related to information systems' requirements for different types. Finally, these different types of information systems are analyzed. It is concluded that: (i) information on customer-order specific products should be distinguished sharply from information on anonymous products; (ii) information systems in the customer-order driven part of the supply chain should first of all support the creation of customer-order specific information by qualified engineers; and (iii) large investments made in products or processes should be reflected in the information system by automatic generation of customer-order specific information.

Keywords: Production management systems, One-of-a-kind production

1. Introduction

1.1. Why one-of-a-kind?

The theory of production management covers such different issues as quality control, logistics control, efficiency control, human resources management, process innovation, and so on. These issues are usually treated as if production were a repeating activity, yielding anonymous products. Quality control is based on measuring techniques which assume repetition. Logistics control is based on forecasting, lot sizes, safety stocks, etc., which assumes repetition. The theory of production management is largely a theory of producing anonymous products.

There is nothing wrong with producing anonymous products. For example, the benefits of early industrialization were largely due to the fact that parts were interchangeable. However, it is worthwhile to note that one-of-a-kind production has not raised much interest in the past, although it may be a most important form of production in the future, for two reasons.

Firstly, the markets of consumer goods show an increase in variety and a decrease in product life cycle. This means that producers of these goods move more and more towards one-of-a-kind production. In addition, tailoring the product to the customer's needs is increasingly important in quality improvement. Ultimately, this leads to one-of-a-kind production (OKP).

Secondly, the innovation and redesign of production processes becomes a considerable activity in many plants. A chemical process plant employs typically 20% of its direct labour in an OKP machine shop involved in redesigning the main plant. The situation is equally common for plants with repetitive manufacturing of discrete consumer goods.
1.2. Information systems for production management

Analogous to the theory of production control, information systems for production management are mostly based on anonymous production. In the last decades, these systems have become widely available by means of standard software packages. Usually, these packages are based on the assumption that the interesting areas of production are not driven by customer orders. Typically, manufacturing resources planning (MRP II) is used as the main frame of reference. Sometimes, the ideas from MRP II are modified in order to suit the needs of repetitive manufacturing such as advocated by the just-in-time (JIT) approach.

These information systems are based on the assumption that perfect information is a prerequisite for manufacturing and that management is mainly a matter of rational decision making. However, in OKP the situation is often the opposite. Perfect information is only available after the project is finished, and management means motivating professionals to act like a team.

1.3. Outline of the paper

We conclude from the above discussion that there is a need for knowledge development in production management systems for one-of-a-kind production. Thus, this paper focusses on OKP.

In the next section, the nature of OKP is investigated by means of a typology of production situations. Section 3 proceeds with a characterization of management problems in several types of OKP, focussing on production management.

Section 4 discusses consequences for information systems. The paper’s conclusions are presented in Section 5.

2. A typology of production situations

In order to develop a typology of production situations, we have to introduce first of all the notion of the customer order decoupling point (CODP). The CODP refers to the point in the material flow from where customer-order driven activities take place. Stated differently, the activities upstream of the CODP are driven by planning activities based on forecasts, rather than on firm customer orders. The concept of CODP is illustrated in Fig. 1, which is derived from Hoekstra and Romme [1]. Different places of the CODP give rise to quite different production situations. We will not elaborate in this paper on physical distribution. Therefore, the first position of the CODP is neglected in the remainder of this paper.

Apart from the CODP, there is a second point which is important in understanding one-of-a-kind production. This point is illustrated in Fig. 2. It is concerned with the amount of investments made in developing products or production processes independently of the customer order. A company is called product-oriented if it has made considerable investments in product development independently of customer orders. A company is called workflow-oriented (or process-oriented) if it has made considerable investments in production process development independently of the customer order. A production process consists of all manufacturing steps required to produce a particular family of products. Of course, there exist companies which are both product-oriented and workflow-oriented. A company is called resource-oriented (or capability-oriented), if it has invested considerably in resources (humans, machinery) but not necessarily in specific processes or products.

These concepts are less obvious and less well known. A few examples are therefore necessary to illustrate the point.

Consider an aircraft-producing company. Such a company has invested billions of dollars in developing products without having a customer order. Nevertheless, companies producing air-
Crafts are usually willing and able to add some customer-order driven engineering to each individual aeroplane which is sold to a customer. Therefore, an aircraft company is a product-oriented engineer-to-order company.

The situation is different for an aerospace company that produces satellites. A satellite is built completely customer-order driven. However, satellites are built by companies having the capability to build these first time right. Such a company is a resource-oriented engineer-to-order company.

Finally, consider a printing company specialized in weekly periodicals. If this company is able to take care weekly of the detailed layout and all preparatory work, as well as the printing and finishing and even the distribution of such periodicals, it is a workflow-oriented engineer-to-order company. On the other hand if a company contracts all kind of printing work as a flexible and ad-hoc subcontractor, it is a resource-oriented company.

A similar distinction can be made for make-to-order businesses. At first glance, a mechanical repair shop seems to be quite similar to a machine-tool manufacturer. However, the machine-tool manufacturer has usually developed his machine tools independently of any customer orders, whereas repair work is customer-order driven make-to-order business. Many specialized subcontractors, such as foundries, find themselves in the same position as repair shops. Thus, foundries and repair shops are resource-oriented make-to-order companies, whereas machine-tool manufacturers tend to be product-oriented.

Semi-process industry, such as paper manufacturing, is often workflow-oriented make-to-order business. This type of industry has made high investments in the production process for a well-defined family of products.

A similar explanation can be given for assemble-to-order business. There are products such as trucks, which require a considerable investment...
in product development by the supplier before customers can be approached. For this reason, a truck manufacturing company is a product-oriented assemble-to-order company. (Note by the way, that truck assembly is usually also a workflow-oriented business.) There are other products, such as houses and other real estate, where the supplier of these products has not made any investment in product development or process development independently of the customer orders. For this reason, construction companies are usually resource-oriented assemble-to-order companies, at least in The Netherlands. Again, workflow-oriented assemble-to-order business is found for example in semi-process industries, such as the production of alloyed steel.

This should be sufficient to explain the different types of order-driven business and "one-of-a-kind" which are indicated in Fig. 2. For the sake of completeness, we have also added some examples of make-to-stock companies with different orientations.

In the following sections of this paper, the typology of Fig. 2 will be used to describe the differences in production management systems for different types of OKP production situations.

3. The nature of production management in different types of OKP

3.1. Introduction

In order to keep the discussion within the size of a paper, we shall consider only three types:
- product-oriented assemble-to-order business ("trucks");
- capability-oriented make-to-order business ("foundry");
- product-oriented engineer-to-order business ("aircraft").

These three types will be discussed in the next three subsections. The discussion is summarized in Fig. 3. For the sake of completeness, this figure also shows a comparison with the product-oriented make-to-stock business ("commodities")

<table>
<thead>
<tr>
<th>CODP</th>
<th>Engineer to Order</th>
<th>Make to Order</th>
<th>Assemble to Order</th>
<th>Make to Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-management's focus is on:</td>
<td>Customer order contracts</td>
<td>Capacities</td>
<td>Innovation</td>
<td>Marketing/distribution</td>
</tr>
<tr>
<td>Uncertainty of operations is concentrated in:</td>
<td>Product specifications</td>
<td>Production processes</td>
<td>Mix of orders</td>
<td>Product Life-Cycles</td>
</tr>
<tr>
<td>Complexity of operations is concentrated in:</td>
<td>Engineering</td>
<td>Component manufacturing</td>
<td>Assembly</td>
<td>Physical distribution</td>
</tr>
<tr>
<td>Middle management's focus is on:</td>
<td>Project-management</td>
<td>Subcontracting, Shop Floor Control</td>
<td>Master Production Scheduling and customer order contracts</td>
<td>Stock control</td>
</tr>
<tr>
<td>Information systems i.e. P.M. are focused on:</td>
<td>Support of Product Engineering</td>
<td>Support of Manufacturing Engineering</td>
<td>Support of material supply and order entry</td>
<td>Support of forecasting and stock control</td>
</tr>
<tr>
<td>Nature of IS oriented towards</td>
<td>Generative solutions</td>
<td>Reference solutions</td>
<td>Rules</td>
<td>Decision support</td>
</tr>
</tbody>
</table>

Fig. 3. Characteristics of different types of one-of-a-kind production.
in order to be able to highlight the peculiarities of one-of-a-kind.

3.2. Production management problems in assemble-to-order

When a product-oriented company offers its products in an assemble-to-order mode, there is a heavy competition on the variety of products which is offered to the customers. This means, usually, that product families are under continuous pressure for increasing variety and innovation. Therefore, innovation is a top-management concern. Slow innovation leads to loss of market share, whereas unconstrained innovation leads to quality problems and high costs.

In such an environment, operations management faces much uncertainty in forecasting the mix of customer orders which will be obtained. Therefore, it is very difficult to procure the right materials and to install the right capacities beforehand. Thus, assembly of always varying customer orders is the most complex operation. This holds in particular in situations where material supply is not perfect, where customers change their requirements and where engineers change the specifications of the product—all at the same time.

Therefore, middle management in production is focussing on the balance between material supply, capacity availability, and customer-order entry. Ideas from flow production and just-in-time can be used to ensure capacity availability and short-term material availability. Long-term material supply can be supported by master production scheduling in combination with intelligent product modelling (see Section 4.2).

Customer-order entry requires a number of steps which should be supported by information technology, such as checking for consistency of the customer's wishes, generating bills-of-material, manufacturing instructions and other engineering documents, calculating the costs, and quoting delivery dates based on the MPS. All these functions will be discussed in more detail in Subsection 4.2.

3.3. Production management problems in make-to-order, capability-oriented companies

The make-to-order business to be discussed here is assumed to be a capability-oriented company. The market situation for make-to-order companies is usually more uncertain than for assemble-to-order companies. This is due to the fact that there is no product available which can be marketed or forecasted. The customers approach the company because of its reputation in production capability, price, responsiveness or service. Top management is focussing on capacity and capability: capacity creation, capability improvement, capacity maintenance, and selling capacity and capability. There is a strong need for a simple, rough capacity planning and monitoring system.

The uncertainty of the operations is usually concentrated on the question how much effort the production process for a particular job will take. Some companies avoid the risk which is caused by this uncertainty. These companies do not sell a product or service to their customers, but the capacity itself. In Bertrand et al. [2] such a company is called a capacity selling production situation.

In a typical production situation, the complexity of the make-to-order business is usually concentrated in component manufacturing. Often, these production companies have limited capacity themselves in order to limit their fixed costs. Consequently, there is a tendency to accept more work than available capacity allows, and to subcontract part of the work. Therefore, middle management in production is focussing on shop floor control and subcontracting. Such issues as lead-time control and efficiency are quite important. In many cases, some form of project management and project control is implemented in order to provide service to the customer. However, sophisticated planning and scheduling tools are seldom a success because of the many uncertainties: reliable and skilled personnel which is used to teamwork without avoiding responsibilities is in many cases a better guarantee for success. In other words, selling capacity in a make to order business is connected to an appropriate human resources management.

As mentioned, much uncertainty on the shop floor is due to a lack of reliable engineering data about the operations of new orders. Therefore, information systems which support manufacturing engineering are most useful. Note that such systems are completely different from the material-oriented information systems known from
3.4. Production management problems in engineer-to-order, product-oriented business

When discussing engineer-to-order in this paper, we concentrate on engineer-to-order business with a significant product development, independent of customer orders. In this type of business, the product strategy should be formulated explicitly, and communicated throughout the company. The product strategy specifies which features or components of a product family can be negotiated about, and within which limits customer demands can be met.

Even if a well-formulated product strategy exists, there is often a considerable amount of interpretation required for each customer order. Each customer order carries the risk of requiring considerable product development in some area, while being sold as a minor variation on a standard product. Because of these risks, top management is usually focusing on the individual contracts with customers.

This type of business faces a fundamental uncertainty about the content of certain customer specifications. Usually, these specifications cannot be investigated in depth during the contract negotiations. Therefore, there remains much uncertainty about the nature of these specifications until the product engineering work is finished.

The cost, the lead time and the quality of the final product are largely determined during the engineering phase. Thus, production management cannot be restricted to management of the operations after the product engineering phase. On the contrary, product engineering is often the most complex operation to be managed.

The focus on product engineering has also another important management consequence. It means that the nature of production planning activities is not primarily material-oriented (as in assemble-to-order) or capacity-oriented (as in make-to-order) but project-oriented (or workflow-oriented). Project management should not be associated with formal planning techniques but rather with mastering the complexity of the customer-order driven activities. This includes e.g. document control, change control, quality control, risk assessment, reuse of experience, and optimal use of human capabilities. An important point here lies in the support of information systems in defining and maintaining standard engineering processes and standard solutions.

3.5. Summary and preliminary conclusion

Summarizing the above, a few general statements can be inferred. When moving from make-to-stock towards engineer-to-order, top-management's concern with individual orders increases. Furthermore, the focus of production management shifts from material-oriented via capacity-oriented towards workflow-oriented. The nature of the uncertainty faced by operations management changes from well-quantified and repeatedly occurring uncertainty towards qualitative and unique types of risks. Consequently, decision support in terms of mathematical models loses its relevance and fast feedback from the engineer-to-order business, production management is highly intertwined with customer-order driven engineering.

There is one conclusion which is not immediately clear from the above, but which is very important for the discussion on information systems in the next section. Generally speaking, the engineer-to-order situation requires very short communication channels between the engineers and the company's top-management. Also, short communication channels between production management and the engineering professionals is required. Thus, the distinction between decision making and execution is in engineer-to-order less clear than in make-to-stock. The engineering professionals which are part of the operational logistic system are largely determining the outcome of decisional processes. This point will be explored in the next section.

4. Information systems for one-of-a-kind production

4.1. Introduction

Within the context of this paper, a complete treatment of information systems supporting production management in OKP is clearly impossible. An introduction can be found in Bertrand et al. [2], Chapter 6. In this paper, some points will
be highlighted which follow from the discussion in the previous section. These points are summarized in Fig. 3. Before discussing information systems in assemble-to-order, make-to-order, and engineer-to-order in more detail it is illustrative to characterize information systems for make-to-stock.

Typical information systems for make-to-stock situations are MRP systems in production and DRP systems in physical distribution. These systems measure the flow of products and the flow of orders in terms of *anonymous products*. These products and their inventories are assumed to exist independently of customer orders.

The aim of MRP-I and DRP-I is to generate automatically planned work-orders for manufacturing or transportation of anonymous products. This leads necessarily to the assumption, that engineering data and logistics data are complete, consistent and correct. In one-of-a-kind business, the highest aim of an information system is not automatic generation of planned work-orders, but user-friendly support of engineering professionals. This will be argued below.

4.2. Information systems for assemble-to-order production

In assemble-to-order production, the goods-flow consists of two parts. The part upstream of the customer order decoupling point (CODP) has much resemblance with make-to-stock production, and the information system resembles the make-to-stock information systems just described. The part downstream of the CODP is quite different, and will be described first. We shall make a distinction between transaction processing and decision support.

4.2.1. Transaction processing

As for transaction processing, an important requirement is the following. It should be possible to trace the goodsflow in terms of customer orders rather than in terms of anonymous product codes. There are several reasons for this statement.

First of all, in assemble-to-order business the number of possible final products within one family is usually far too large to make anonymous codes for final products useful. Therefore, the goodsflow should be measured and traced in terms of a customer order, and not in terms of an anonymous code number.

Furthermore, a product code is a shorthand for a completely specified product, both in terms of the wishes of the customer and in terms of the supplier's technology. However, product innovation is usually so fast that the same set of customer's wishes can often be realized with different technical realizations. This choice should not complicate the sales process. Thus, codes for customer's wishes should not be mixed up with a particular technical realization. Anonymous codes are harmful here.

Finally, if the customer changes his wishes in one way or another, the processing of differences is quite easy if the customer's wishes are kept as the ultimate specifications. It becomes quite difficult if the original customer order and its changed version have to be transformed to anonymous code numbers. More discussion about this point can be found in Bertrand et al. [2], Chapter 6.

4.2.2. Decision support

As for decision support, two interacting and difficult decision have to be taken in assemble-to-order. On the one hand, material supply has to be provided for—long before firm customer orders are available. On the other hand, customer-order entry should be supported, presumably in relation to the materials and capacities which are being supplied.

The first decision has been located in the master production schedule by MRP literature [3]. This approach states that the customer's choices can be clustered into orthogonal features which each have a number of options. The MPS for the options can be derived from the production plan for the family as a whole by using the so-called *planning BOM*. The components of the product family should base their gross requirements on the MPS for the options according to the planning bills-of-material.

This approach has been implemented in many MRP software packages. As an approach for material supply, it can be criticized. However, there are not so many alternatives, except for no coordination of components at all. As an approach for handling variety in assembly and distribution, it has many drawbacks. An alternative which is also often encountered, are so-called parameter-driven variant BOMs. These systems select the appropri-
ate documents. Recently, a more general approach is emerging, where bills-of-material, routings, instructions, and other documents are generated rather than selected. This approach looks rather promising [4,5]. In both approaches, the operations are supported by many rules which makes rule-based systems quite likely. These rules should ultimately influence the material supply planning process.

The other important decision, customer-order acceptance, should also be supported by appropriate software. First of all, the wishes of the customer should be checked for completeness and compatibility.

Next, the resource requirements of this particular customer order should be generated, and compared with the availability. This leads to a proposed due date and price. However, the acceptance of a particular customer order may hamper the acceptance of other orders, thus making the order unattractive. Consequently, a priority should be given to the order. All the above computations are in nature rule-based systems.

4.2.3. Summary

Summarizing the above discussion, the following can be stated about information systems for product-oriented assemble-to-order firms:
- it should be possible to trace the goods flow and the order flow based on the customer order and specs;
- customer-order specific documentation should be generated automatically;
- rule-based systems supporting professional engineers are likely to be more in place than optimization routines supporting decision makers.

4.3. Information systems for make-to-order production

Let us shortly recall what Section 3.3 revealed about capability-oriented make-to-order companies. These companies focus at top-management level on capacity. Production management concentrates on issues such as manufacturing engineering, shop floor control, and subcontracting. Rough planning is required to support negotiations with customers, and detailed planning is required for managing the capacity load and for subcontracting. In all these cases, manufacturing engineering is essential in order to get information about the relevant capacity requirement. Therefore, the key element in information systems lies in the support of manufacturing engineering.

4.3.1. A reference base with manufacturing engineering data

Information systems supporting manufacturing engineering should provide tools for quick data entry at various levels.

Consider first the level of rough planning. Networks with activities for projects which are in the negotiation phase should be created fast, and should be modified easily. For capability-oriented companies, it is unlikely that such networks will be generated automatically. Rather, there should be a database with former projects which may act as a starting point for engineers to create a new project. It goes without saying, that a database with reference networks should be maintained carefully in order to guarantee that this "reference base" contains the accumulated best experience in the company. It should prevent future projects from making the same mistakes as earlier projects.

The same is true at the level of detailed planning. Again, information systems should act as toolkits in order to make manufacturing instructions and routings readily available. Fast production of these documents enables the company to take subcontracting decisions at an early stage. Automatic generation of these documents will seldom be possible because the company is capability-oriented, but the existence of a reference base with applicable solutions and with intelligent software support becomes within reach of many companies.

When designing and using such a reference base, many ideas from group technology can be implemented in a new way. For example, the idea creating a routing for a particular part by selecting some manufacturing steps from the routing of an imaginary part with maximal complexity. Or the idea of combining different parts in one work order with one routing.

Group technology is closely connected to human resources management on the shop floor. Particularly, the level of detail of work preparation by manufacturing engineers should match the level of skills and the expected amount of
4.4. Information systems for engineer-to-order production

Engineer-to-order production for a product-oriented company has been characterized as follows in Section 3.4. Top management is focussed on customer-order acceptance. Operational management is focussed on customer-order specific engineering activities. Reuse of knowledge and capitalization of experience is a key-issue here. Therefore, engineer-to-order is largely relying on people, and human resources management is a most important aspect of management.

For a product-oriented company it may be expected that there is a limited set of well-defined engineering activities. Usually, a product family in an engineer-to-order business offers a number of functions in various degrees of standardization. Some functions are standard without any variants being offered. For example, the engines in an aeroplane are probably not subject to negotiation. Other functions are standard with some variants being offered. For example, the place of the doors in an aeroplane may be customer specific in terms of a few predefined variants. Still other functions could be offered with several variants, but with the additional possibility of customerspecific design. In an aeroplane, this could hold for the kitchen. Finally, there may exist functions which have to be designed customer-order driven, such as the aeroplane's interior.

A suitable information system for engineer-to-order production should be able to support the engineering activities sketched in the list above. It should be able to generate a project network for each customer order, specify deliverables at various milestones, estimate costs, etc.

In addition, the information system should make a careful distinction between customer-order specific information and customer-order independent information. Customer-order independent information should contain the latest product standards, the accepted solutions, and be the basis for generating many (customer-order specific) engineering documents.

Customer-order specific information may contain many elements which should never enter the standards, and it should be frozen after the order has been finished. The best ideas may be retained for further reference purposes as in the make-to-order situation, but they should be investigated in depth, before they can be taken into consideration for inclusion in the standards. Clearly, the information system should support this functionality.

The information system in engineer-to-order companies should support the existence of incomplete and sometimes inconsistent or ambiguous information during the design phases. Incompleteness is clear: after all, complete documentation is the result of design. Inconsistency or ambiguity arises if some engineers take assumptions about the outcomes of other engineering activities although they know that these assumptions will turn out to be false. In such situations it is far more important that an information system can signal and support a temporary inconsistency than that it would force consistency. The same holds for ambiguity.

4.4.1. Summary

In engineer-to-order business, the actual operations start with engineering activities. Therefore, the information system should act first of all as a tool for engineers, supporting them in project definition, reuse of experience, cost estimation, etcetera.

This means furthermore that the traditional distinction between an information system and a logistics system (or executional system) disappears to some extent. This distinction is suggested often, and can be depicted elegantly in a form as in Fig. 4 (drived from Doumeingts [6]).

The executional system employs the information system as its production machine for producing deliverables. Therefore, the information system and the executional system start to overlap. However, as we have argued in the previous Section, the executional system and the decisional system also start to overlap. Therefore, Fig. 5 is perhaps a better illustration of engineer-to-order business than Fig. 4.

Finally, we may formulate another conclusion, about the nature of appropriate information systems themselves. In product-oriented engineer-to-order companies the system should support automatic generation of engineering documents. This holds particularly for the documents which
describe the project-nature of the customer order.

5. Conclusion

Concluding the above discussion, we may state the following:
- information on customer-order specific products should be distinguished sharply from information on anonymous products;
- information systems in the customer-order driven part of the supply chain should first of all support the creation of customer-order specific information by qualified engineers;
- large investments made in products or processes should be reflected in the information system by automatic generation of customer-order specific information.

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