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FOF PRODUCTION THEORY:
TOWARDS AN INTEGRATED THEORY FOR
ONE-OF-A-KIND PRODUCTION

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SUMMARY

The Basic Research action 3143 "FOF PRODUCTION THEORY" aims at integration of various scientific disciplines involved in the design of production systems. The project is limited to one-of-a-kind production, and the project is especially interested in computer integrated manufacturing (CIM).

The central idea is, that the alternatives available in redesigning a factory cross the boundaries of established scientific or engineering disciplines. Therefore, these alternatives or "design choices" play a major role in our approach. Similarly, the performance indicators which measure the suitability of a redesign, cross the boundaries of established disciplines. Consequently, the FOF project focusses on these performance indicators as well.

The relationship between design choices and performance indicators is modelled in a qualitative manner by a so-called connectance model. This model is implemented in a tool called REMBRANDT, which allows us to browse through available design theory. Detailed knowledge of relations between design choices and performance indicators is being developed in a number of so-called drawing models. These drawing models are quantitative in nature, and can be fed with data from actual companies.

1. ONE-OF-A-KIND PRODUCTION AND CIM

The markets for consumer goods are characterized nowadays by an increase of variety, while at the same time showing steadily decreasing product life-cycles. Improved delivery performance for short and unpredictable life-cycles is only possible with small batches. In addition, tailoring the product to the individual customer's needs is increasingly important in quality improvement. This tendency also results in production in small batches, which are often driven by customer orders. Ultimately, this leads to one-of-a-kind production.

Traditionally, one-of-a-kind production (OKP) has been associated with capital goods. However, European producers have shown a poor delivery performance, which resulted in a loss of market share in branches of industry such as shipbuilding (see Burbidge (1)). Consequently, the general public does not associate OKP with the future of European industry, but with its history. Hopefully, this is a misunderstanding of the general public.

The fact that consumer goods production itself moves towards OKP is only half of the story. In addition, the innovation and redesign of the production process is in many plants a considerable activity. It is not uncommon nowadays, to find a repetitive manufacturing production site employing 10%-15% of its direct labour in an OKP machine shop involved in redesigning the repetitive factory. No doubt, the real issue in such plants is the performance of such an OKP-system.
There seems to be a common agreement that future production systems should be more "integrated" than the level of integration which is obtainable by now. Unfortunately, there is much less agreement about the meaning of the term "integration". This term is often used in connection with Computer Integrated Manufacturing, CIM. For proper understanding of integration of scientific disciplines aiming at the design of production systems, it makes sense to consider the term CIM first.

Figure 1 shows the CIM-architecture which is central in many papers about CIM. In this picture, the three bubbles at the ridge of the circle have something in common: these bubbles represent established business processes in most organizations. The bubble at the heart symbolizes integration, but it is different from the other three bubbles: this bubble merely suggests that, if the business processes are supported by information technology, these processes can exchange messages between computerized subsystems. In other words, the business processes are all connected to each other by some way of automated communication.

The main direction for improvement of today's factories lies in improved interaction between business processes. Each business process should give due recognition to the impact of its own actions on other business processes. Techniques like "design for production" or "design for logistics" are important examples for illustrating the need for interaction between business processes. This may be paraphrased as "Human Integrated Manufacturing". It is not our intention to deny the importance of information technology here. On the contrary, we believe that information technology enables us to obtain a much higher degree of interaction between business processes. However, the goal is not to have a fully automated factory, but to have full support of communication between interacting business processes. We shall use the term "integrated manufacturing system" to denote interacting business processes, giving due recognition to the impact of their actions for the performance of other business processes.

Figure 1. CIM-architecture (derived from Gunn (2)).
Now consider the design of such an integrated production system. Several questions emerge immediately. Firstly, what is the object, i.e., what is being designed? Is it the plant layout or the local area network? Is it the decision-making structure or the salary system? Secondly, what are the objectives of a design? In other words, which perceived performance criteria play a role in such a design activity? Thirdly, how do we know, that a particular design will yield a particular performance? In other words, what is the scientific status of our design activities? Fourthly, how can we design a series of small steps in redesigning an existing factory in a desired direction? Fifthly, who is the designer? Is it an outside person, making clean rational calculations, or is it the organization itself, who is involved in redesign?

To help answer the preceding questions, the FOF project aims at developing a designer's workbench. In an integrated design, it is necessary to organize our knowledge. This means, that the objects of design, the performance criteria, and relationships known from different scientific disciplines has to be brought together into an organized set of models. This is, in essence, our idea about integration. The workbench will allow experimenting with a number of design choices to test, design or redesign a manufacturing system. The effect changes in design choices will have, is measured on a set of performance indicators.

2. TYPOLOGY OF OKP

In many cases it is convenient to regard one of a kind production as consisting of a number of operations. At an aggregate level, the following operations might typically apply:
- Design
- Process planning
- Component production
- Assembly

The two first are frequently referred to as engineering, and the two latter as production. Engineering and production comprise both processes of major interest.

Including the management type of operations, the manufacturing company can be regarded as consisting of three interdependent processes. This is illustrated in Figure 2. A process is defined as a set of related operations performed on, or in connection with, a flow of concrete or abstract items. In Figure 2 the processes are:
- Production
- Engineering
- Management

![Figure 2. Processes in an OKP System.](image-url)
Production is connected to a flow of materials. The purpose of production is to transform raw materials into finished products.

Engineering is connected to a flow of technical information, usually represented as drawings or other documents. The purpose of engineering is to provide technical specifications on what products to produce and how to produce the products.

Management is connected to a flow of operational information, usually represented in the form of work orders or planning or status documents. The purpose of management is to release and monitor work orders for production and engineering.

In addition to the information shown in Figure 2, any system will also be exposed to external input, such as f.ex. product demand.

A common distinction of different types of supply systems to the market is the distinction between standard-products supply and customer-order driven supply. However, customer-order driven supply encloses a number of different situations. For example, shipbuilders, maintenance shops, construction companies, and automotive component subcontractors may all be considered as customer-order driven suppliers. These production systems are so different, that a typology is needed.

Basically, a typology may be derived by following a customer order through an OKP factory. At an aggregate level the operations performed are as mentioned above (design, process planning, component production, assembly). In principle, each of these operations may be based on a standard solution of a customer order. This will give 24 combinations. The combinations may in practice be larger, since the mentioned operations may be of different type for each product or even component.

The complexity may be even larger, taking into account that engineering fall into different categories dependent on what is selected as input basis:

- Engineer from scratch
- Engineer from components
- Engineer from product

For this report is sufficient to review a simplified classification, limiting strongly the number of alternatives, as developed by Wortmann (3). This paper distinguishes the following two questions in order to create a typology (the typology is shown with examples in Figure 3):

A. Which activities in the primary process are customer-order driven?
B. Which investments (in e.g., product-design, resources, procedures, or supporting activities) are customer-order independent?

Based on question A, a well-known dimension emerges, viz.:

A1. Make to stock: only distribution is customer-order driven
A2. Assemble to order: assembly and distribution are customer-order driven
A3. Make to order: purchasing, component manufacturing, assembly and distribution are customer-order driven
A4. Engineer to order: even (part of the) product design is customer-order driven

Based on question B, a much less known dimension emerges, viz.:

B1. Product-oriented systems: these systems supply the market with products which have been designed (to some extent) independently of existing customer orders
B2. Capability-oriented systems: these systems offer particular skills or resources, but not predefined products, to the market.
As always with typologies of companies, many companies do not fit neatly into this scheme. Usually, this is because a company may produce different product families or operate on different markets. This leads to different positions in Figure 3. However, Figure 3 illustrates the variety of situations which might be covered by the term "one-of-a-kind".

3. CURRENTLY AVAILABLE KNOWLEDGE ON OKP-SYSTEMS

In the remainder of this report, we will concentrate on column A4 and row B1 of Figure 3, unless explicitly stated otherwise. The last decade has shown an affluent wave of literature on engineering, production and production management. Unfortunately, nearly all material is rooted in the production of standard products (row B1, columns A1 and A2 of Figure 2). As argued in Bertrand et al (5), a production control system such as MRP II is based on standard products, produced in (large) batches. The OPT system is even more based on column A1 of Figure 2.

A production system design philosophy such as Just-in-Time (JIT) production, originates from automotive industry. It carries many elements which are relevant for line-assembly only. The same holds for Total Quality Control (TQC). Anyone who tries to apply these concepts to engineering design work is struck by the implicit assumption of standard products. This is true even for a book which takes distance from technicalities and details (such as Garvin (6)).

Computer Integrated Manufacturing (CIM) is another field where claims of applicability to OKP are suspect. Gunn (2), for example, stresses the fact that CIM has to go together with TQC and JIT. We will argue that information technology can contribute considerably to OKP-systems’ performance, but not in the same way as elsewhere.

Theories on product design (such as Wheelwright and Sasser (7)) are typically focusing on customer-order independent design (for an overview, see Sederholm (8); the general nature of design is discussed in Takala (9)). Although this is certainly valuable, it is not dealing with one of a kind production. Here, again, there seems to be a lack of interest in current literature.

A notable exception is the literature on Group Technology. Burbidge (1) is focusing explicitly on engineering companies. However, the ideas of Group Technology are mainly described for component manufacturing. In fact, the close connection of Group Technology to Period Batch Control, advocated by Burbidge, suggests that the majority of the parts produced are standard parts. However, many ideas from Group Technology are formulated in quite a general way. Therefore, the attempt to specify Group Technology for OKP seems worth while.

It is evident that full scale Just In Time or Optimized Production Technology is inappropriate for OKP systems. However, it is possible to apply some major elements of JIT (such as elimination of waste, in-time deliveries over the total logistic chain, set-up time reduction, good control over the process, co-makership, Total Quality Control, multiskilled
personnel, internal standardization, information systems to manage changes, preventive maintenance) successfully in OKP systems.

The same observation applies also with OPT. The fundamental idea to make a distinction with the activation of a resource vs. the beneficial use of a resource is valid in any type of a manufacturing system. In designing production management systems also the bottleneck approach is appropriate and can thereby simplify production management of an OKP system.

There is another wide misunderstanding of the potential of CIM technology in OKP industry. According to this CIM investments are oriented towards repetitive manufacturing, exclusively. However, without CAD / CAM the OKP companies are doomed to be eternally blamed for long throughput times, high overall costs, poor quality, slow reaction and long and poor delivery performance. Fortunately, there are some symptoms that this misunderstanding is loosing its pace.

When considering theories of production organization, such as JIT, GT, or socio-technical design, there seems to be at least three "paradigms" or views which have to be synthesized. Each of these views provides ways to describe an existing or hypothesized production system. Each view relates design alternatives to performance indicators. Therefore, each view presents an evaluation of an existing production system with respect to particular performance indicators. These views are:

- A framework with theories about the appropriate way to structure the workflow through a factory. This workflow is not restricted to "physical" transformation of material. These theories lead to a structure of the workflow which is closely connected to an organizational structure in terms of departments, groups, task forces, teams, etc. (This is the workflow view mentioned in chapter 1)
- A framework with theories about the internal structure of the resources. In component manufacturing, this structure consists of the physical layout, the equipment, the task structure of individuals and groups. In OKP, and especially in customer-order driven engineering, the human aspect seems to be most important. (This is the resource view mentioned in chapter 1)
- A framework with theories about decision making. In OKP it seems that the boundaries between decision making and other activities (such as design) are less strict than elsewhere. (This is the organizational / decisional view mentioned in chapter 1)

A comparison of OKP and repetitive manufacturing is done in Table 1 (Falster (11)):

<table>
<thead>
<tr>
<th>Manufacturing</th>
<th>Management</th>
<th>Engineering</th>
<th>Info Tech</th>
<th>Resource</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetitive</td>
<td>JIT</td>
<td>Workst</td>
<td>CAD</td>
<td>Machine</td>
<td>Functional / Line / Groups</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NC</td>
<td>CAM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-of-a-kind</td>
<td>CIT</td>
<td>Comm</td>
<td>CIM</td>
<td>Human</td>
<td>Groups</td>
</tr>
</tbody>
</table>

JIT = Just In Time
CIT = Concurrent in Time, e.g. Concurrent Engineering

Table 1. Comparison of key elements in One-of-a-Kind and Repetitive Manufacturing.
4. TOWARDS AN INTEGRATED THEORY

Redesign is an interactive pattern of activities where the scope and focus change frequently. This means that OKP design choices should be tackled at different layers. The three levels adopted in our basic model are the following:

1. **Strategy**
2. **Structure**
3. **Operations**.

The highest layer (strategy) deals with the strategies to be adopted and the inherent competition factors. It also deals with the economics (particularly long term) of the manufacturing systems. Typical design choices to be made at this layer are listed below (cmp. e.g. Hayes and Wheelwright, 1985 (28)):

- market niche (customer specified / modified vs. standard; brand vs. bulk; cost minimization vs. differentiation)
- product technology (mechanics, electronics, software, ...)
- process technology (scale, flexibility, dedication)
- facilities (location, size, specialization)
- integration (vertical, horizontal, extent, balance)
- suppliers (number, structure, relations, make / buy)
- human resources (selection, training, compensation, security)
- quality (image, responsibilities).

The intermediate layer (structure) deals with the production system as such, i.e. its components (primitive system) and the relationships between them (restrictions). Some typical design choices at the structural layer are:

- products
- resources
- manufacturing layout
- organization

The layer of operations deals with decisions how the inputs of the manufacturing system are applied to the structural manufacturing system. Some typical design choices at the operational layer are:

- operative and medium term decision rules and criteria
- operative and medium term management functions.

The operational input fall into two categories:

- demand pattern
- supply pattern.

The demand pattern is represented as the customer order flow while the supply pattern is resulted from the availability of subcontractors, material suppliers and the resources of the business unit itself.

In any layer of the total conceptual model some of the design choices remain fixed, while free choice can be exercised over the others. There are also situational conditions (such as demand pattern) more or less given at each layer. Because of the hierarchy of the layers there are most degrees of freedom at the highest layer (strategy), because both structural and operational design choices are at least in principles open. On the contrary, when making operational design choices both the strategic and structural layers are more or less fixed.

Fixed design choices and situational conditions are together called the frame conditions in our total model.
5. DC-PI NETWORK

When the designer takes a large scope, (s)he tends to be more focused on strategic management issues. At strategic level, a designer with a wide scope needs to navigate carefully through theoretical cause-and-effect chains before selecting a particular promising area, suitable for a close up.

In the remainder of this chapter, it will become clear, that such a means of navigation has been developed. It connects design choices (DCs) to performance indicators (Pis), and it will be called therefore the DCPI network (see chapter 14). It has the form of a so-called connectance model (Burbidge, 1984 (17), Eloranta, 1981 (29), Karni, 1990 (30)). The theoretical background of connectance models is in the soft systems science (e.g. Checkland, 1985, (31)), which has been applied, e.g. on the research of the future, in qualitative economics as well as in qualitative simulation. The type of relationships implemented in the FOF model are the following:
- Affects (is affected by)
- Is element of (has element)
- Increases (is increased by)
- Decreases (is decreased by)

Because of the variety of the permitted relationships, the mathematical properties and thereby the reasonable operations in the connectance model are scarce. Transitivity, e.g., is limited to just a few types of relationships.

![DC-PI Network Diagram](image)

Figure 4. Sample from the DC-PI network in REMBRANDT.

At the structural or the operational layer, when the designer takes a more narrow scope, there emerges a need for more precise modeling of relationships between design choices and
performance indicators, eventually based on situational factors. These more precise models are
called relationship models. Relationship models are often quantitative models. Such quantitative
models for parts of factories are usually implemented as simulation models. These models are
still relating design choices to performance indicators, but they do not claim to be
comprehensive.

Simulation models and other relationship models can be fed with actual descriptive data
about the factory to be redesigned. Therefore, relationship models should be distinguished in:

- Reference relationship models (general theories and knowledge)
- Particular relationship models (company selected knowledge, data and facts)

Finally, there is one advantage of the architecture above which is worthwhile to notify.
In principle, the structure of the DCPI network and the various drawing models is such that it
can be maintained if our knowledge about the (OKP) manufacturing systems grow. More
explicitly, the DCPI network is represented in a tool called REMBRANDT. Part of this
network is presented in Figure 4 above.

6. THE FOF DESIGN FRAMEWORK

The design framework is based on two pillars (Falster (11)):
1. Descriptive production theory which originated in resources/workflow modelling, the
so-called Walrasian production model and its generalization to dynamic modelling of
control/decisions/organization based on control theory and the GRAI Grid.
2. Theory of factory (re)design (Takala 15).

This framework exists at two different levels:
A - The level of reference models
B - The level of particular models.

This split in reference and particular models are in line with the ESPRIT CIM-OSA
model (26). Reference models represent available theory. These models link general design
choices via intermediate variables to general performance indicators. They may give due
recognition to the existence of situational factors, but these models claim to be generalizations
over such situational factors. Particular models represent an abstract example of a particular
case or an existing or conceived real-life situation. These models show particular design
choices which have been made in a particular case. They enable the designer to specify
alternatives for these design choices, and to compute the consequences of these alternatives
within a limited domain of knowledge.

The reference model can be split on two sub-levels, A1 and A2. In the theoretical
framework these levels represent:
A1 - The primitive system, i.e., the various components of the system.
A2 - The constraints, i.e., how the system components are connected together (topology of
the system).

In the design framework the counterpart to the primitive system is denoted an entity
model. An entity model thus represents a description scheme for a particular real-life situation
by design choices and performance indicators (Falster (11)). The counterpart to the
constraints is called a relationship model (see section 5). The relationship model has several
layers of detail. The top layer is constituted by the DCPI network. Links in the network can be
replaced by more detailed, quantitative models, in an open architecture. The relationship model
represents a heuristic to interconnect design choices, performance indicators and
intermediate/independent variables of the entity model (Falster (11)).

In summary, the design framework includes, as indicated in figure 5:
- Design reference model consisting of an entity model and a relationship model
- Relationship models consist of more detailed, quantitative reference relationship
models
- Particular models, based on reference relationship models fed with actual data
In figure 6 the design reference model is explained.

**Figure 5 Models and views in the design framework.**

**Figure 6. Views and basic data structures in a Design Reference Model.**
All models may be seen from any of the three views:
- Workflow
- Resource
- Organizational/decisional

We are now in a position to explain more about the detailed relationship models. Such a relationship model contains limited data (Pis and DCs), and it models only a subset or a limited part of the total OKP system. Relationship models may comprise a view, part of a view, or may even contain parts of several views. A relationship model can be used as a template to describe a particular piece of reality in a quantitative way. We distinguish between reference relationship models and particular relationship models. The difference is that a reference relationship model will operate on variables, while the particular relationship model is fed with values of these variables.

In the top part of the figure the design reference model is shown. In the middle part the design reference model is sliced into views and an entity model (DC, PI) and a relationship model (RM) is shown for each view. In the lower part the views connectance to the basic data structures are shown as well as vertical decomposition of the GRAI grid.

The aim of the workflow view is to describe the primary flow, grouping of resources and products/work. These may be based on group technology (factory flow analysis and departmental flow analysis). The aim of the resource view is to describe the internal structure of teams of humans. The aim of the decisional view is to describe the decisional flow and logic in a multilevel hierarchy.

The FOF project is dealing with both the engineering and production processes within the OKP system. We consider engineering processes as similar to production processes. In other words, engineering work produces output which is planned and delivered in the same way as materials are.

The output of this engineering work, "paperwork", documents, or better: information, can be managed according to known principles in production. The information-producing nature of engineering output, will enable the use of IT in managing the timing of the output. This sheds a new light on CIM in OKP.

7. SIMULATION MODELS

The components of a design reference model are depicted in figure 7. The idea is that design choices (DC) are changed. The effect on the OKP system is measured by the performance indicators (PI). The DCPI network referred to in section 5, defines the relationship between DCs and PIs.

The design choices are made about (for example) physical layout, sociotechnical structure, functional structure, decision hierarchy and responsibility, or organisation. Design alternatives could be functional, process, or group layout, hierarchical or autonomous group structure etc. The aim of design choices is getting a better factory.

Better is measured in terms of the performance indicators that are deemed relevant for this decision. Performance indicators could be efficiency, quality of working life, decision stability, etc.

A relationship exists between each design choice and its relevant performance indicators. These relationships, obtained from theory or empiry, are expressed in models (relationship models). It is the task of the modeler, to specify these relationship models, and with that, to indicate the relationship between a design choice and its performance indicators.

In designing/redesigning or testing a manufacturing or production system while using relationship models, some information is given as input. This is basically the products to be delivered and the resources that the company have available. Both may be inadequately,
insufficiently or only partly defined. They may all be changed or modified in the process of designing or redesigning the manufacturing system.

![Diagram](image)

**Figure 7. Components of a Design Reference Model.**

The company exists to satisfy a requirement for products from its customers. This demand pattern is also assumed to be one of the basic input data of relationship models describing a part of the manufacturing system.

Finally, the company may operate different working hours on different resources. The operating hours is another basic input data, of the same type as demand.

All these input data can be categorized into either design choices or experimental input.

The design choices define a model of the production system as such, i.e., its components (primitive system) and relationships between them (restrictions). Some typical structural design choices are:

- Products
- Resources
- Production layout
- Resource organization
- Decision rules and criteria
- Management functions

The experimental input defines the input applied to a model of the production system. This input falls in two categories:

- Demand pattern
- Supply pattern

The demand pattern is the customer orders and the supply pattern defines the availability of subcontractors, suppliers and the working hours of the company's resources.

In designing/redesigning the system while using a relationship model, the various structural design choices are changed to demonstrate different performance. The performance is measured by performance indicators. In testing the system the structural design choices are kept fixed, while the operational design choices are changed and applied to measure different...
performance. Testing is to check how the structural system responds to different operational conditions.

In any application of the model some design choices and input parameters remain fixed, while others are varied. The set of fixed design choices and input parameters for a specific application is referred to as the frame conditions under which the model is used.

In summary, the use of the model is visualized in Figure 5 (Rolstadás (4)).

![Diagram: Input/output in Operation of a Relationship Model of an OKP System.]

There may be only one relationship model built into one simulation model, and there may be many relationship models built into one simulation model.

It is preferred to implement several relationship models into a single simulation model. This makes programming and execution more efficient, and insures that the characteristics of the same production systems are the basis of many evaluations. It is not possible, however, to achieve the implementation of all relations into a single simulation model.

There are three types of relationship models: Analytic, dynamic, and event based. These types of models must be implemented in three different types of simulation models and tools.

Models differ in the method of calculation that is required to evaluate the relationships between Design Choices (DCs) and Performance Indicators (PIs). From this viewpoint there are three types of relationships, and therefore three types of required simulation tools:

- The relationships between some DCs and PIs can be evaluated with analytic models. Tools for the evaluation of this type of relationships could be spreadsheets or other single shot calculation tools.
- The relationships between some DCs and PIs can only be evaluated with continuous dynamic models. This is the case when there are feedbacks, and time dependent effects. Tools for the evaluation of this type of relationships could be Stella, Dynamo, or other multi period evaluations models.
- The relationships between some DCs and PIs can only be evaluated with discrete event models. This is the case when characteristics of the individual events have an impact on the behaviour of the system, and need to be taken into account during evaluation. Time dependent effects also play a role. Tools for the evaluation of this type of relationships could be GPSS, Taylor, Exspect, or other event driven simulation tools.

Characteristics of the models that make the use of several simulation models per tool necessary are the time scales on which choices are made, and the impact of DCs on PIs takes effect. It is not useful to evaluate effects that take place on different time scales in the same model.

8. CONCLUSIONS

The value of the FOF conceptual model is that performance indicators from various fields of study can be related to the same design choice. This allows an interdisciplinary, multi-criteria evaluation of a design choice.

There may be relationship models that connect only one design choice with one performance indicator, there may be relationship models that connect a single design choice with several performance criteria, and there may be relationship models that connect many design choices with many performance indicators. A single design choice may influence one or many models. A single performance indicator may appear in one or many models.
The simulation models are implementations of the relationship models in some executable tool, such that design alternatives can be evaluated.

The FOF aim of making an IT based designer's workbench requires that the relationship models can be used in computers. To this end, the relationship models are built into simulation models. These simulation models can then be executed to evaluate design alternatives.

The various simulation models will be provided as a collection of software systems designed within the project. The main purpose of this software will be to provide a demonstrator that will demonstrate the achievements of our project towards an integrated theory.

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