Process Networks Engineering: Modeling Decentralized Factories

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Abstract Competitive advantages of manufacturing strategies can only be achieved by designing corporate structures and processes purposefully. Instead of improving production methods individually, which in any case are usually highly developed, they should be linked together into an efficient complete process. Material flow, manufacturing, and inspection processes must not be treated separately, but have to be seen as part of a complex system. Since information flow is a crucial factor for process performance, it must not be neglected in production models. Information processes are not only additional processes in a system; they also interact with other production processes. This can be described as a control loop. By means of modeling and simulation based on a control loop element, it is possible to analyze, systematically develop, verify and implement structures and processes of decentralized production systems.

1. THE TASK: MODELING DECENTRALIZED FACTORIES

Holonic or Intelligent Manufacturing Systems, Modular Organization, Fractal Factories, Virtual Companies, Lean Manufacturing and other concepts of decentralized production have one basic concept in common: Largely **autonomous organizational units** manufacture products and services and exchange them via well-defined interfaces in a **network** (fig. 1).

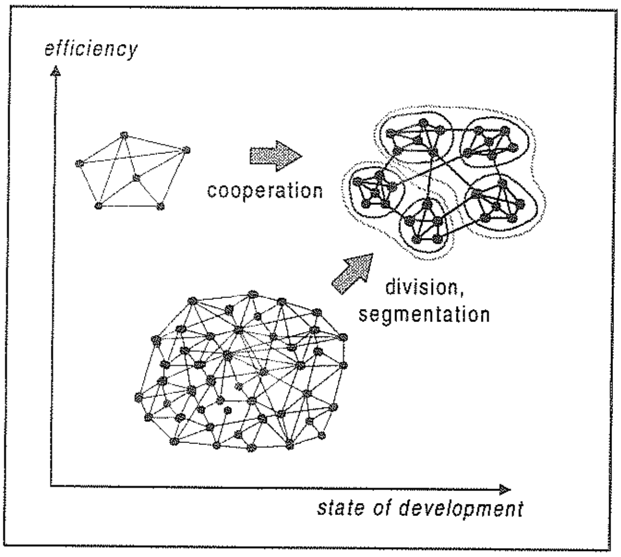

Figure 1: Decentralized factories

Resources required for production are available in each unit and can be utilized efficiently and effectively due to self-controlling mechanisms *within* the subsystem.

Interfaces *between* organizational units are designed to enable an exchange of products and services without frictional loss. Thus, the individual units themselves, as well as the whole system are particularly productive.

Concepts of decentralized production apply to a broad range of organizations. In order to fit the specific case, basic concepts need to be **tailored**. Starting with an analysis of customers' needs, market structures, core competencies and corporate objectives, management must develop a *vision* in order to carry out the initial idea for reorganization. On this basis, a framework of requirements for technical, organizational and personnel-related process conditions has to be derived. This is not yet a specific applicable solution. But how can a company find one? Whereas there are impressive case studies in management literature, the basic concepts themselves are usually quite general and give no specific *guidelines for implementation*. Therefore, development and implementation of tailored solutions is up to management and experts of process modeling.

2. THE SUBJECT: QUALITY PROCESS MODELING

World-class organizations are process-oriented, i. e., their structure is focused on the support of corporate production of products and services, as well as conducting process assessments regularly. On the other hand, processes in common enterprises have never been planned systematically, or they have changed over time, so that structure and process are not suitable anymore.

Depending on specific conditions and objectives, there are numerous **degrees of freedom** for the quality oriented design of production systems and processes, regarding e. g.:

- the *origin* of quality (single steps and links in the value chain)

- the *proof* of quality (inspection strategies within the process) or
- the *control* of quality (management and coordination of processes)

Concepts of decentralized production make use of a wide range of instruments from various scientific disciplines. But they still need to establish a general method of their own. A system for the integration of indirect tasks is notably missing, namely, an answer to: Which tasks should be executed centrally, which in decentralized units?

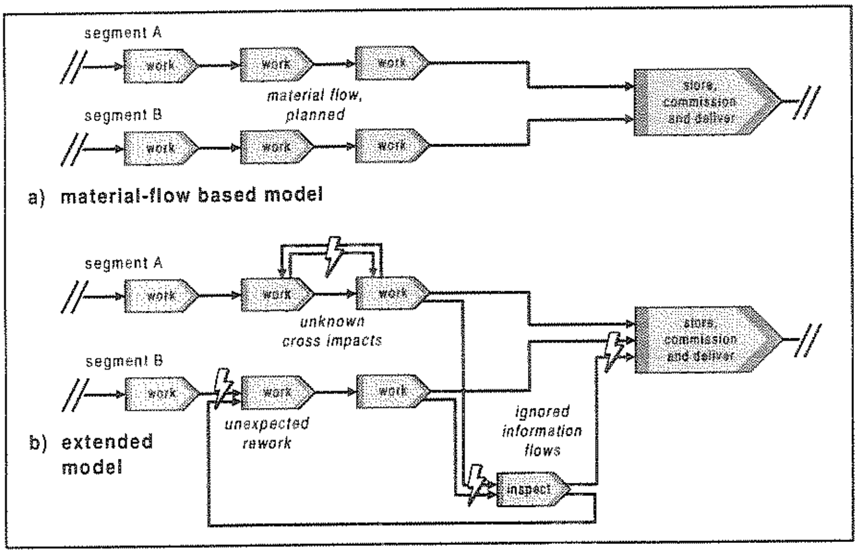

Figure 2: Extended models of production processes take quality aspects into consideration

State-of-the-art concepts of process design usually consider material flow (or work flow), but neglect important **cross impacts:** the network of manufacturing processes and aspects of inspection are treated separately. For instance, product related data (CAD/CAM/CAQ) and order related data (PPC) are usually treated separately. This means that available information and potential know-how is not utilized. Models of production like material flow simulation or applications of PPC, if not based upon a quality model, also neglect these interrelations. An insufficient model, however, causes unsatisfactory results of planning and trouble in production (fig. 2):

- Product characteristics can be produced in a *single* activity, in a *series* of activities (sub-process), or by *combining* the results of two or more activities. Whereas connections in material and work flow are obvious, there are many interrelations with less evidence: Activities can influence each other or have effects on remote sub-processes. These hidden impacts are a major cause for trouble in production processes.
- Pure (material flow) simulation and most PPC systems ignore measuring equipment. Time consuming inspection in test laboratories or *bottleneck* capacities of special measuring equipment like 3D measuring machines can cause delay to processes.
- Deviations of quality characteristics can cause trouble in current production programs: *Rework* is likely to occupy machines needed for other orders. Eventually, *substitute* orders have to be written and considered in PPC. This affects not only schedules: If lot sizes are lower than usual, inspection plans must be updated, too.

Similar interrelations exist in every organization. Due to organizational autonomy and spatial separation in decentralized production systems, their effects are potentially stronger than in common organizations. As a consequence, many tasks of planning and simulation require a more differentiated, but still manageable process model.

3. REQUIREMENTS AND OBJECTIVES OF PROCESS MODELING

Comprehensive Production Process Models have to support the three **main areas** of process management: Process *planning* determines the logical order of activities. Furthermore, decisions about responsibilities and interfaces have to be made. Process *control* has to identify characteristics of repetitive processes in order to meet specifications. Process *improvement* both raises performance and reduces deviations.

Table 1: Performance objectives in decentralized production systems (examples)

	internal: performance	**external:** competitiveness
speed	cycle time, process time	delivery lead time
dependability	reliable operation	on time delivery to customers
costs	total productivity	price, costs of transaction
quality	scrap, error-free processes, rework	quality of product, delivery, use
quantities	stock, work in progress, throughput	output, delivery lot size

flexibility	lot size, use of capacity	product range (variants), delivery

These tasks have to fit in a **system of objectives**, covering aspects of time, costs, and quality. In decentralized production systems, these objectives have both *internal* aspects (regarding production of products and services) and *external* aspects of exchange between sub-systems or customers and suppliers respectively (table 1).

4. THE CONCEPT: CONTROL-LOOP-BASED PROCESS MODELING (C/PM)

Production structures can be regarded as a **system,** that is a defined set of elements with relations. Therefore it is irrelevant for the mere *definition* of units, whether they are intra-corporate or inter-company decentralized production systems. The real *differences* are found in special requirements for logistics, which are obvious due to the distance between cooperating plants, and also in the basis for cooperation, which is ruled by market mechanisms on the one hand and by organizational structures of power on the other.

Relations between elements make up a **process**. Its behavior can be described in terms of cybernetics, whose elementary basis is a **control loop**: After executing an activity, the result is being checked and compared to the set point in order to affect the process purposefully. The categories *„execute - check - compare - affect"* can describe every activity in an organization. Thus, „system", „process" and „control loop" make up a simple universal model, which can be used for the description, analysis and design of corporate processes. When applied to decentralized production systems, four different **kinds of control loop** can be distinguished (fig. 3):

- In *production*, manufacturing process data or product characteristics are being compared to the desired value in order to affect the production process. **Process control loops** are, for example, process control in the narrow (technological) sense, inspection or statistical process control (SPC).

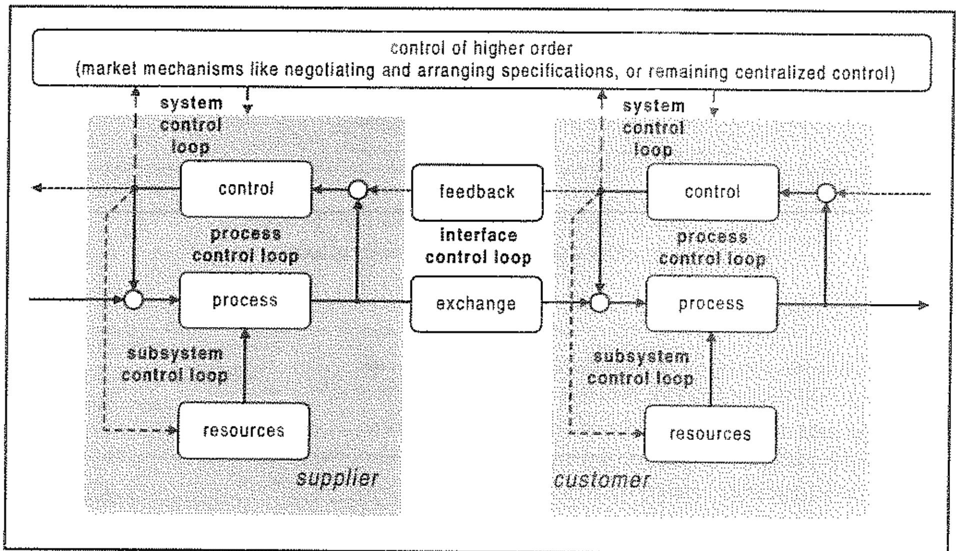

Figure 3: General control loop model of decentralized production (simplified)

- For each exchange of products (material, energy, information) or services, the recipient can give feedback to the supplier regarding the condition of products or their delivery. Delivery and feedback make up a control loop in a figurative sense. **Interface control loops** are, for example, raw materials delivery, acceptance inspection and corresponding payment or even complaints.
- Experience in production often leads to measures of improvement. They usually affect the process by changes of *resources* such as machines or devices, by the design of work systems (ergonomics) or by new general know-how, like procedures, work schedules, recipes, or qualification of employees. Autonomous organizational units can carry out improvements on their own (**subsystem control loops**), for example as part of a continuous improvement process. This leads to higher productivity, shorter cycle time, less stock and work in progress, less scrap and rework.
- Even the *structure* of decentralized production systems and the *cooperation* of organizational units is being controlled. Negotiating contracts, strategically selecting and assessing suppliers, jointly developing new products and processes or solving problems in mutual task forces, exchanging employees and information make up what has been defined as **system control loops**.

To conclude, production and interface control loops represent *everyday work*, whereas subsystem and system control loops describe processes of *change* within decentralized production systems. Thus, organizational learning, learning from the customer and learning in market structures can be regarded as control loops in a more figurative sense.

To summarize, these four general kinds of control loop can describe all business processes. They are the basic **constituents** for modeling complex structures and processes of decentralized production systems as **hierarchically nested control loops**.

5. APPLICATION OF THE CONCEPT: RESULTS

c/pm *modular* and *hierarchical* design method links **different levels** of production in one general model: *cooperation* of various companies and plants, single *units* of the production system, single *orders* (material flow and process level) and the level of *machines* and single *activities*. Thus, production and exchange of products can be described with all aspects of cooperation like interrelations (including the hidden ones) and interfaces.

The model can also be used in **different phases**, from the first idea, the concept, specification and implementation phase to everyday work in business processes. This supports the main areas of process planning, control and improvement. In particular, this facilitates not only the analysis of sophisticated cause-and-effect mechanisms, but also the prediction of how changes in manufacturing or inspection processes lead to better, easier and more robust procedures, as well as what their effect is on quality, time, and costs.

Applying c/pm in industrial projects is used to verify and validate *concepts* of decentralized production systems. Since the simple model makes complex systems easy to understand, it supports implementation and management of new organizational structures. Moreover, c/pm allows to develop *specific solutions* as well as general *rules for the design* of decentralized factories.

So far, c/pm has been applied in the metal-processing, mechanical engineering and chemical industries for various problems:

- Reengineering administrative processes like order processing;
- Reorganization of logistics and value chains in modular production;
- Improvement of incoming goods process and reliability of assembly processes;
- Analysis of manufacturing processes and design of autonomous production cells;
- Development and simulation of inspection strategies (manufacturing, in-process and final inspection).

Improvements achieved are of a magnitude known from reengineering-projects. The most striking results are **process improvements**: Typically, cycle time could be cut by up to 60 %. Along with process precision, dependability has been improved too (roughly 20 % more on time deliveries in the process and to the customer). Less machining or process time and better schedules lead to an increase in productivity (about 25 %) and to a reduction of stock and work in progress, but at a higher availability. A reduction of non-control and multiple control prevents processes from trouble. This leads to higher product quality (up to 80 % less scrap and rework) and employees' motivation and satisfaction are better. All in all, the essential benefit of the application is both an increase in flexibility and a significant reduction of costs.

Along with process improvements, **technological improvements** could be achieved. Manufacturing and inspection activities have been re-arranged in order to be executed at a more suitable position within the whole process context. Hence, processes are more robust and productive. Most processes can even do with less inspections. In distinct, closed control loops, information is available where needed. This develops know-how in all hierarchical levels, from everyday work in the workshop to production controlling and strategic management in the cooperation of plants.

Other **organizational improvements** result from the mere design of control loops: It is possible to derive criteria for the integration of planning and administrative tasks in production areas, to find process structures systematically, determine degrees of autonomy and establish mechanisms of coordination between organizational units.

A first prognosis shows enormous potentials for further, more general improvement. Unlike ad hoc solutions, the system of c/pm purposefully promotes completely new approaches of process design, if processes are not treated as time consuming black box elements. Conclusively, to consider interactions of process and control loop structures is a major prerequisite for the design of decentralized production systems, the prevention of trouble and the creative utilization of organizational complexity.

6. CONCLUSION

Process modeling based on control loops (c/pm) enhances the scope of strategic management by deriving distinct solutions out of general concepts since it is systematically developing and utilizing manageable processes. Modular modeling and distinct use of a wide rage of different methods do not only allow the systematic design of innovative production systems, but also the development of new, powerful PPC, CAQ and simulation software.

A more complex model than the usually considered, pure material flow model is an important prerequisite for the design and management of real-life complexity. Hierarchical and modular model structures support a comprehensive analysis and hence a thorough understanding of hidden interaction in complex systems.

Moreover, this allows to systematically identify possibilities for improvement and innovation. Thus, it is possible to both reduce complexity and utilize its benefits. All in all, significant competitive advantage can be achieved.

Results of research and industrial project experiences in decentralized production systems are summed up in the „**Dortmund Q**" model (fig. 4). It combines advantages of control-loop-based process modeling (reduction, management and utilization of complexity) with the systematic implementation method, which allows the transfer of research results into real-life processes.

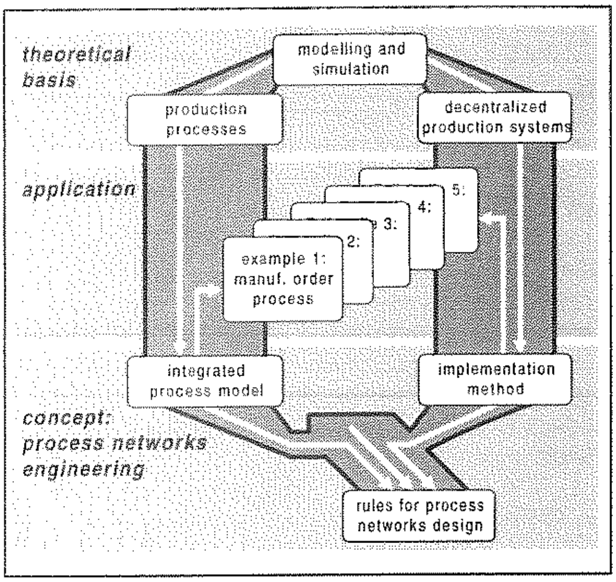

Figure 4: Constituents of the „Dortmund Q"

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