Multi-Agent Systems in Internet based Production Environments — an enabling Infrastructure for Mass Customization

Thorsten Blecker, Günter Graf

Author contacts:

Dr. Thorsten Blecker, Assistant Professor
University of Klagenfurt
Department of Production/Operations Management, Business Logistics and Environmental Management
Universitaetsstr. 65-67
A-9020 Klagenfurt, Austria
+43-(0)463-2700-4077
blecker@ieee.org
http://www.uni-klu.ac.at/plum/

Mag. Günter Graf
University of Klagenfurt
Department of Production/Operations Management, Business Logistics and Environmental Management
Universitaetsstr. 65-67
A-9020 Klagenfurt, Austria
+43-(0)463-2700-4078
guenter.graf@uni-klu.ac.at
http://www.uni-klu.ac.at/plum/

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Abstract: Mass customization manufacturing requires a high level of reconfigurability and flexibility in production – especially in production planning and control –, effective information systems, as well as suitable production concepts. Multi-agent systems theoretically provide the required features, but a lack of informational integration and organizational incompatibilities lead to low applicability. Internet based production concepts provide the necessary interoperability and organizational alignment to support an overall application of multi-agent systems in mass customization. The intended decentralization of organizations in Internet based production concepts conform to the modular structure of multi-agent systems. A coordinated application leads to an enabling of mass customization.

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1 Introduction

Mass Customization aims at the production of individualized products at mass customization efficiency (Pine, 1993). A characteristic of mass customization is the direct interaction between customer and manufacturer during the configuration process. Fast creation of new variants, as well as transparency for the customer is the main requirement for a mass customizing enterprise. Conventional software architectures are insufficient, if operations are closely interlocked, the goals of local actors have to be synchronized with superordinated objectives and concurrently fast reactions on random unpredictable events are necessary for successful acting (Kirn, 2002). Currently we have to realize two technological developments in industrial information systems: The increasing diffusion of Internet Technologies on the shop floor, e.g. in networking dislocated assembly lines, and an accelerated evolution of Multi-Agent Systems (MAS), e.g. in production planning and control. On the one hand, these trends are very important to strengthen competitive advantages of industrial firms in general. Both, formal and empirical studies approved the significant productivity increase of manufacturing processes by using intraorganizational applications based on modern information and communication technologies (Shaw, 2001, Barua/Lee, 2001). On the other hand, Internet Technologies support the evolution and realization of new production systems, based on a direct Internet Protocol (IP) supported networking of machines on the shop floor. Moreover, MAS in industrial processes arise and increase the potential benefits of Internet-technologies on the shop floor.

Both Agent and Internet Technologies are considered as key factors of a mass customizing production system (Baker et al., 1999). Internet-Technologies offer a high connectivity, which is needed for fast and seamless transport of data e.g. from the configurator up to the shop floor. The high number of variants and processes leads to higher complexity, especially in information logistics. This complexity can be managed and reduced by MAS, as shown by Timm et al. (2002). Thus, we show the benefits and implications here of such an infrastructure for mass customizers. Mainly it enables the following features:

- Enhanced planning and control of the production environment
- Reconfigurability of production systems that enables fast integration of new variants
- Seamless information flow from customer to the shop floor that enhances delivery times, reduces costs and enables process transparency for internal purposes, as well as for customers

We assume that the new key Technologies in production are Internet Technology based agent, information and production systems. Therefore, we analyze the effects of the emerging infrastructure for production/operations management (Blecker, 2003a).

This paper addresses the presented infrastructure aspects and derives implications for the successful realization of mass customization in production/operations management. We analyze the effects and outcomes of an integrated view on the complementary (Milgrom/Roberts, 1990) aspects structure and strategy of a mass customizing enterprise with the focus on the production system.

Benefits of this integrated view arise especially for production planning and control and for the reconfiguration of the production environment. The combination of the benefits of MAS Internet based production concepts lead to an enabling of mass customization. Furthermore, we analyze as to whether multi-agent systems within Internet-based environments allow an enabling infrastructure for mass customization. Afterwards we discuss constraints and some implementation necessities for implementation.

2 Multi-Agent Systems in Internet based Production Environments

2.1 Recent Advances in Multi-Agent Systems

Multi-Agent Systems (MAS) have been discussed since 1985, when cooperation among intelligent agents was at first proposed in computer science (Rosenschein, 1985). MAS are part of distributed artificial intelligence, such as cooperative problem solving or blackboard systems. These approaches deal with a priori known, distributed tasks that require intelligent problem solving behavior. The difference compared to other methods of distributed problem solving is the bottom up approach (Kirn, 2002). This means that autonomous intelligent agents that have certain knowledge about their specific domain are trying to reach their goals by cooperating with other intelligent, autonomous agents. Autonomous agents themselves are defined as systems that are situated in and are a part of an environment, as well as sense that environment acts on it over time in pursuit of its own agenda (Franklin/Graesser, 1997).

The advantage of MAS is the possibility to solve partial problems without having to consider the general problem. Intelligent agents know about their specific domain and try to obtain the necessary information or resources to solve the actual problem. The agents have to cooperate with other agents, which can be organized in terms of negotiation, bidding or opportunistic behavior. In several research projects the usefulness of MAS in realistic commercial application scenarios has been investigated (DFG, 2002). Production is one important domain for MAS. Several MAS-based solutions have been developed for complex problems in manufacturing. MAS are analyzed for controlling machines and manufacturing lines to reach a more fault tolerant and more flexible control (Sundermeyer/Bussmann, 2001). Production Management research utilizes MAS-concepts mainly to enhance flexibility and robustness in production planning and control systems. Interorganizational approaches also try to apply the approach for planning and control supply chains and business networks (Turowski, 2002). Mass customizers may use the intended features in different ways (Piller, 2000).

MAS are more precise in planning, scheduling and reconfiguring production processes (Corsten/Gössinger, 1998), respectively the dependent information systems, such as production planning and control. In mass customization, we distinguish between the configuration, scheduling in the production system, integration of new variants into existing processes or the generation of new workflows as relevant fields for the use of agent technology in the production environment. We define the production environment for mass customization as the production system itself and the infrastructure to connect the production system to the customer interface, generally a web-based configurator. The consumer in this concept is also part of the production concept as „prosumer" which means the consumer is directly engaged in the production process, because he/she starts the production with his/her order and determines the attributes of the order (Piller/Moeslein, 2002).

In literature, there are different views of important issues for mass customization. Zipkin (2001) states the logistics, the process flexibility and the elicitation as critical. In our view we have to especially consider process flexibility. Elicitation is not in the scope of this paper, and logistics are only touched upon in internal aspects. This view considers all aspects of mass customization. We are concentrating on production issues. Tseng/Lei/Su (1997) formulate for mass customization production itself the following necessary characteristics:

- Dynamic manufacturing requirements
- Flexible resources
- Postponement of product variety

- Product family architecture
- Flexible process routing

These characteristics define the basic requirements for production in mass customization. Indeed, the characteristics cause higher complexity to run, plan and control than in traditional production systems (Tseng, 1997). Production management needs instruments to handle the complexity in the production system. Information systems are an important issue when dealing with this task. Many researchers argue that traditional ERP-systems cannot cope with highly flexible, dynamic environments (Piller, 2001). Therefore, more adequate information system structures are necessary. MAS may be an approach to design information systems that meet the requirements of production systems in mass customizing companies. Different forms of mass customization exist in practice, reaching from service individualization at the reseller (soft customization) to a full customization of the product, which means that the mass customizer is actually a variant producer (hard customization), but reaches a higher output e.g. by using standardized modules (Piller, 2001; Pine, 1993). The soft-customization, which is not involved with the production itself, is not a field for MAS, because the production itself does not change and conventional information systems are suitable in this case. MAS as a concept that is able to handle complexity by being able to take into consideration much more parameters than monolithic software systems is only useful if there is a large amount of complex information that has to be processed. This is trivial, but the issue is to find the critical point for the usefulness of MAS. Clearly, the hard customizer might reach that point. We are not able to define the exact point, but we can state that there are scenarios when MAS in of an advantage against traditional systems.

Mass customization often requires introduction of new variants and even to remove variants to optimally meet customer requirements on the one hand and to hold costs down on the other hand (Blecker et al., 2003). Therefore, the production system has to quickly adapt to changes in the variant portfolio. Many variants are manageable by the existing configuration of the production system. However, if there are new variants with new parts or processes which are necessary, these changes have to be introduced quickly. Furthermore, mass customizers have to be able to react on customers' requirements that are out of range. MAS may also speed up changes in the material flow system and the machinery by way of reducing the efforts for implementing the changes in the information system. A MAS that controls the material flow system is able to automatically consider a change in the capacity of a machine because it is considering the machine as an autonomous resource that indicates its capacity by itself.

Although there is the ability to support the (re-)configuration of system elements and variants for mass customization, the control of the entire production environment is the most important field for MAS. With a defined number of variants provided, there is much uncertainty in the production because of the random demand for variants. Scheduling and routing in the production system is very complex, because the dilemma between minimized lead times and maximized machine utilization has to always be considered. Under stable conditions, a standard ERP-system is able to optimize the ratio, but if there is a high grade of uncertainty, standard production planning and control concepts are not able to manage the complexity (Corsten/Gössinger, 1998). Additionally, production planning and control in mass customization has to be able to support dynamic changes in production plans in very short intervals, so that the unsteady customer orders may be produced at low costs. Even decentralized PPC approaches cannot manage this, because rush orders require one to change the entire production plan. MAS can recalculate the plan immediately and identify the best alternative.

The benefits of MAS for mass customization are analyzed in several research projects. We can separate existing concepts in interorganizational approaches, which use MAS for the planning in supply chains for mass customizers. Other approaches concentrate on the scheduling or technical aspects in machines, or for use in reconfiguration tasks. The last group builds a full framework for the entire production environment.

Interorganizational focus

Turowski (2002) uses agents for so-called macro-processes in interorganizational mass customization scenarios. He suggests the use of an Internet-based approach for EDI to allow automated supply processes. Agents negotiate terms of shipment, prices based on actions within the mass customization company. The approach shows the possibility to implement intercompany mass customization processes even if customization is partially completed by suppliers. This approach does not take into account the necessary structures and processes in the mass customizer company. Turowski simplifies the process from configuration to the order at suppliers to one action of an agent. This can only be true if parts of the mass customized products are completely produced by suppliers and only assembled by the mass customizer. To implement interorganizational cooperation for the execution of mass customization-processes based on agent systems, the use of component-oriented implementation based on Internet-Technologies is necessary (Turowski, 2002).

Control focus

Another automation based approach originates from the PABADIS project (Pabadis, 2000) which concentrates on the shop floor and is also assumed to be advantageous for mass customization (Penya/Bratoukhine/Sauter, 2003). Agents are used for the integration of ERP-systems and automation systems in the field area. The concept differs from other agent usage scenarios in production environments because of its emphasis on the explicit consideration of the product in the agent system. They suggest agent systems that model not only functions, machines and resources, but also the product itself. The problem for mass customization is the concentration on the field area. Although the authors (Penya/Sauter, 2003) propagate their system as suitable for mass customization, it is not designed for mass customization. It is just a concept that may be used by mass customizing companies in the plant to better organize the complex production processes. Several concepts have been developed to assist the production planning and control functions in a managerial sense, which means that there is a focus on the efficient routing of lots respectively single units in workshop manufacturing. Corsten and Gössinger (2000) propagate an opportunistic scheduling (Fox/Kempf, 1985) with the help of blackboard systems, which are centralized structures that contain the agenda of MAS. The project IntaPS (Timm et al., 2001) also uses intelligent agents for small and medium sized enterprises to enhance their cooperation capabilities, but they also demonstrate the application of MAS in production planning and control. Because it is an approach for small and medium sized enterprises, they concentrate on information logistics from the production to the partners and how to find the ideal partner for certain tasks.

Full framework

Two other approaches model the entire production system as MAS. Tseng (1997) presented a market-oriented approach, where the entire production system is controlled through bidding procedures executed by intelligent agents (aggregated to job and resource agents). These agents cooperate similarly to real markets, where prices are created by auctioning mechanisms. The model uses the common approach of the contract-net protocol (see e.g. Sandholm, 2000), where agents bid on jobs and resources to fulfill their tasks. Tseng suggests integrating certain attributes of mass customization manufacturing into the price mechanism. A similar, but more precise approach was developed within the AARIA project. Based on a decentralized manufacturing structure, agents are distributed throughout the production system. There is a distinction between persistent and transistent agents. Transistent agents are created by persistent agents (Baker/Van Dyke/Kutluhan, 1999), e.g. to represent a necessary job or process. The system is controlled through a KANBAN-similar pull system, where the first step is the customer order, which triggers further steps (materials handling etc.) to schedule the necessary sub-processes. Brokers are negotiating between the steps within the production systems by a so-called least-cost scheduling.

The presented approaches expend huge efforts in developing efficient coordination mechanisms, but they all neglect an aligning of the MAS systems with the organization and information structures. This leads to a low applicability of Multi-Agent Systems in production environments. We assume Internet based environments as an ideal basis for the application of MAS in mass customization. Therefore, we analyzed current approaches to Internet-based production. These concepts demonstrate the general usefulness and applicability of Internet based infrastructures.

2.2 Internet based Production Concepts

Usually we understand the term Internet Technologies in the context of the well-known Internet as the technological basis of global information and a communication network. However, the term „Internet Technologies" does not prejudge an external relevance. The term Internet Technologies describes a family of technologies suitable for exchanging structured data about package-oriented transmissions on heterogeneous platforms, in particular protocols, programming languages, hardware, and software. Yet, the internal application of these technologies focuses on Intranets for office information systems. In the future, the main industrial application area for Internet Technologies is in Field Area Networks (FAN). This means the interconnection, as well as networking of automation infrastructure and machine controls on the shop floor (Blecker/Haber, 2001).

Yet, fieldbuses as a traditional, but competing network technology are still dominating in production processes, e.g. the ProfiBus concept of Siemens. In the future, Internet based FAN will complement or even replace fieldbuses. Since 1985, industrial firms have utilized Ethernet on the shop floor. Due to new standards, Industrial Ethernet reduces the technological limits that have existed up to now to the applicability of Internet based FAN or even the replacement of fieldbuses. Industrial Ethernet is based on the relevant international standards (e.g. IEEE 802.3). It is adjusted to the specific environmental conditions, for example regarding electromagnetic compatibility, shaking, moisture, and chemical resistance (Siemens, 1999). In some sectors Ethernet and Industrial Ethernet are already the de facto standards, e.g. in the automotive industry, process industry and in plant engineering.

The technological improvement of Industrial Ethernet and/or Internet Technologies in general does not necessarily enable a total replacement of fieldbuses. On the one hand, some applications or existing machinery still need FAN based on fieldbuses. On the other hand, fieldbuses such as ProfiBus evolve towards a convergent, interconnective infrastructure, e.g. as in ProfiNet. Hence, even where Ethernet cannot replace fieldbuses, Internet Technologies connect the different assembly lines together and transfer detailed data from the shop floor to the office et vice versa. Consequently, a comprehensive application of Internet based FAN enables the expansion of existing Intranets in office automation to all production processes, especially manufacturing. Enabling technologies, such as Web Services, Active Technologies, and Industrial Frameworks (based on .NET or Sun ONE), will support intelligent manufacturing technologies and a homogeneous network from office to manufacturing. These platforms have an enormous potential to reduce (transaction) costs within the production system

(Blecker, 2003b). Therefore, Internet Technologies will become an ubiquitous network respectively an omni-present information infrastructure in the complete industrial firm.

In sum, Internet based Field Area Networks (FAN) may connect office information systems with the automation and control level of every assembly line. It is not surprising that applications of Internet Technologies in production processes increase and that many automation technology suppliers combine Internet Technologies with their products. This leads to a convergence of the traditional production systems and Internet Technologies (Blecker, 2001). It explicates the unification of technologies with different features to a homogeneous service bundle, which enables the revision of traditional Production Concepts or even the development of new Production Concepts.

The considerable advantages of Internet Technologies are uncontroversial for the technological infrastructure of communications and information in production processes. According to Atherton's (1999) idea *Java-based applications* should support planning and control of all production processes. In this scenario Internet Technologies integrate the technical CAx-systems with the economical Enterprise Resource Planning (ERP). This means that Java connects different technological environments and acts as a gateway between automation technology and information technology.

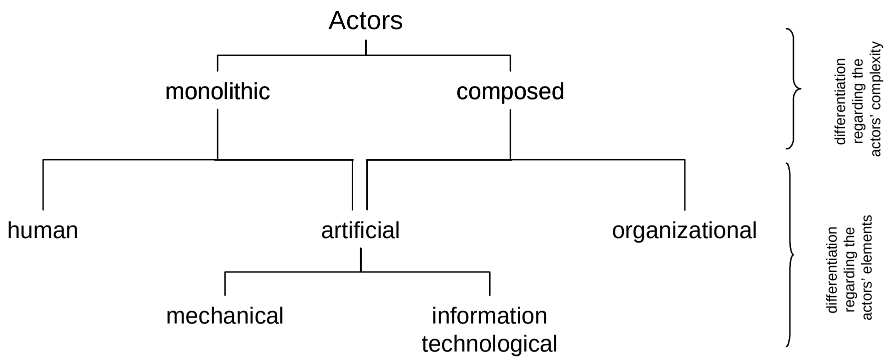
The *Information-Based Manufacturing* shows a higher reference to production processes. This approach describes as a guiding idea a highly information-dependent production, which is distributed throughout several enterprises. As the aimed conditions, it refers a strong customer relationship, a high velocity of (re)actions, networking of decentralized production processes and synchronized demands (Shaw, 2001, pp. 8). Information-Based Manufacturing recommends build-to-order concepts, supply chain coordination and optimal information sharing. Companies must have agent systems, decentralized planning and operation systems, as well as integrated information and automation technologies in the dislocated production processes for the realization of Information-Based Manufacturing (e.g. Veeramani/Wang, 2001).

Approaches for the application of Internet Technologies in manufacturing are observable in the context of the keyword '*Web-Integrated Manufacturing*' in engineering research. Web-Integrated Manufacturing describes the general application of Internet Technologies in manufacturing, for example, agent based systems, Java, Jini and SOAP (e.g. Kuehnle/Klostermeyer/Lorentz, 2001). Even the international research project "plant automation based on distributed systems" (http://www.pabadis.org/) uses this approach as a theoretical basis. The project goal is the application of decentralized, distributed systems of office communication within the machine control on the shop floor in order to survive within turbulent environments. This is supposed to lead to certain intended conditions, namely highly flexible, adaptive and simply reconfigurable production systems. Reconfigurable production systems combine the respective advantages of high-productive and high-flexible systems, because they may be adapted immediately regarding their structure, functionality, and capacity, as well as their inherent technology to demands that have changed. For the realization of this scenario, this approach recommends distributed computing and distributed problem solving in automation on the shop floor. Therefore, the instruments of Web-Integrated Manufacturing focus on a decentralized agent system in manufacturing and embedded systems in automation technologies.

Additionally, Huang/Mak use the term *Web-Integrated Manufacturing* during the preparation of a special edition of the International Journal of Computer Integrated Manufacturing. Both Huang/Mak (2001, 2003) as also the other contributors to this journal only describe individual, dislocated applications based on Internet Technologies for product design and manufacturing. Therefore, the main idea of this approach is the application of interorganizational CAx-technologies, especially CAD/CAM systems, e.g. for the distributed product design (Chang/Pan/Harrison, 2001).

2.3 An Actors Perspective on Internet based Production Environments and their Consequences on Multi-Agent Systems

The application of Internet based concepts in general supports a distribution of decision rights directly onto the shop floor. This allows the employees on the shop floor to act more autonomously. Additionally, the decentralized computation power enhances decision abilities. The embedded computers in machines and facilities enable them to act autonomously. However, the different production concepts deal with the behavior and interaction of actors, e.g. entire companies or employees, in economic systems. In order to apply modularized, Internet based concepts to production management, it is useful to speak about actors referring to autonomous acting units within the production system, which often endue local computational intelligence. Therefore, humans, machines and combinations of them can be seen as autonomous actors in the production system (Blecker, 2003a). The autonomy originates from the distribution of decision rights and the use of decentralized computation power. As shown in fig. 1 we differentiate three types of actors in production systems.



Source: Blecker (2003a), p. 14

Figure 1: Actors in Production Systems

The first type consists of human actors, e.g. planners and workers. Because of the increasing integration of modern information and communication technologies into automation systems and their growing local „intelligence", artificial actors build up the second type of actors in production systems. For example, facilities with embedded computational intelligence may act autonomously in a production process. As in human actors, they perform different tasks and interact with other actors in the production system under physical and cognitive limitations. The third type of actors consists of composed units. We call this type organizational actors, because they consist of a varying number of human and/or artificial actors following organizational principles, e.g. autonomous or virtual teams on the shop floor, and act as a whole.

The actors of the production system have a broad set of abilities to build up relationships with other actors. Thus, we can claim, that every actor may interact with every other actor. These interactions can range from simple data transfer to complex coordination processes. Additionally, the interaction of actors is not limited to the production system, which means that they can communicate with actors outside the production system. We assume that qualities and capabilities of each actor change by applying Internet Technologies for their interconnection on the shop floor, as well as by converging various technologies. Additionally, a decisive influence of modifications of the actors' capabilities and/or of their coactions on operations management is conjecturable. The exact content of coordination between the different actors, their organization and interaction in general, determine the physical and economic output of the production system.

This paradigm is similar to agent-oriented views on information systems. Yu (2001) suggest to model agents with intentionality, autonomy, sociality, contingent identity and boundaries, strategic reflectivity as well as rational self-interest. In an economical perspective, agents are discussed in an institutional approach analyzing especially the information exchange problems between agents. In multi-agent manufacturing systems, agents may represent single resources (a work cell, a machine, a tool, a worker involved in a process, etc.) as well as products, customers or providers (Reaidy/ Massotte/Diep, 2003). For example, Reinhart (1997) already proposed so-called autonomous production systems in which human and artificial agents act cooperatively and widely independent of central production planning and control.

The actors in our model of actors can also be viewed as agents. Computer science approaches model Agents by the Actor formalism. Implementations are typically just implementations of actor systems (Gul/Jamali/Varela, 2001). We understand agents as a specific role of an actor in the production environment. Actors act on behalf of another actor, are called agents, still having the same attributes and abilities as before. Therefore, a multi agent system consists of a number of interdependent actors that are acting on behalf of other actors. They all have a specific role of an agent. Additionally, only information technological actors may be agents in MAS. However artificial or human actors cooperate with actors (playing the role of agents) in the MAS, but cannot be a part of MAS. The proposed notion of actors is also useful for analyzing the advantages that exist with having MAS in Internet based environments for mass customization.

3 Consequences for Production Systems in Mass Customization

Internet based environments allow a matching between organizational structures and intelligent agent approaches. In the literature, this is discussed as fit of organization and information systems. For example, in production planning and control this fit is necessary, because without a decentralized production planning and operation, the „autonomy of the decentralized units exists only on paper“ (Reiss, 1998). Thus, MAS are especially useful in decentralized structures. This does require organizing the entire company with decentralized principles as a necessity – but MAS will only be useful in decentralized parts of the company. MAS are especially important in operations. The presented advantages in production environments arise especially from the fit between organizational principles, managerial concepts information systems structure, and used technologies (Wall, 1998). This fit applies for the modularized units in the production environment, as well as for the multidirectional communication/coordination channels. Therefore, we analyzed the usefulness of a „fitting” infrastructure for production planning and control and for the reconfiguration of production systems in mass customization.

3.1 Production Planning and Control

Mass customizers produce their customized variants by starting some tasks or the assembling of pre-manufactured modules directly after customers order. This requires flexible and adaptive production processes and facilities. Contrariwise, mass customizers should be organized just as a mass producer is that has the ability to manufacture large amounts of goods. Selling is directly dependant upon market demand, but a part of the facilities has to run and produce steadily to be profitable. To have the necessary parts and modules for customization available, a mass customizer could e.g. enlarge inventories, which is not desirable. Alternatively, mass customizers have to optimize their organization especially including planning and control concepts, to meet the requirements of the customization. Producing the desired variants requires flexible machinery as competent employees. The problem is to find e.g. an acceptable machine load and to determine completion dates. The high number of variants requires a more detailed scheduling and routing of the customer orders in the production system. Most approaches try to allocate the necessary tasks and resources after splitting up part and tasks lists. This approach is hardly applicable in mass customization. The conditions' precedents for optimal production planning and control are first of all functioning information processes within the operation subsystem (Kurbel, 1999). Mass Customization is especially because of the huge number of variants and orders pretentious for the information processes. Therefore, efficient production planning and control requires a concept that allows handling the high number of orders, which have a high grade of uncertainty and have rarely the same attributes. Conventional production planning and control concepts are not designed to cope with such a situation; they are either designed for a large number of similar orders (mass production) or for a small number of different orders (job shop production). Both are often based on the MRP II approach, which is applicable for both cases, but the MRP II approach has a centralistic focus. Zelewski (1998) summarizes the problems with central coordination concepts for production planning and control, under a control failure, a motivation failure and a implementation failure.

The *control failure* relates to the problems of centralistic production planning and control concepts if there are uncertain conditions or unsteady demands, summarized in the literature under „turbulence". MRP II-based production planning systems were often criticized for not being able to produce optimal results. This is because of the successive planning structures that do not allow any adequate reaction to changes in lower planning layers (Steven, 2000). Additionally, central concepts get „nervous" when they have to deal with planning shocks, which means that the production planning and control system is not able to adapt to changes in the order situation or loss/change of production e.g. machine breakdown. Especially in mass customization these scenarios occur frequently. To cover the problems of centralistic (MRP II-based) approaches several decentralized planning techniques were developed, but mainly for use in the job of shop production (Corsten/Gössinger, 1998). Therefore, we have a lack of techniques for a high number of variants with higher production quantities, if MRP II-techniques are not adequate. MAS respectively the negotiation-based generation of a production plan by MAS are likely to be suitable for mass customizing purposes. The independency of actors makes the planning more fault tolerant, because they can react independently without having to coordinate with a central authority.

Furthermore, central production planning and control systems cause a *motivation failure*, because the actors in the production system have no freedom for semi-autonomous planning. Especially in the complex planning and controlling in mass customizing companies, a decentralized planning would enhance overall planning capabilities, if adequate communication and coordination structures are provided. This is necessary, because a decentralized planning requires coordination with other actors that have decentralized decision competences. Therefore, the actors in the operation subsystem should be enabled for processing of the information corresponding to production planning and control locally. The decentralized information processing capacity of the agents postulated allow the required information quality, as well as quantity. Autonomous, intelligent software agents may process much of these communication efforts. Software agents are inherently designed for executing information and coordination tasks. Therefore, agents in Internet based mass customization systems may take over coordination actions as was presented by Corsten (1998) and Zelewski (1999). Internet-based agents may also interact with human actors over an interface, so that these agents support the human actors or obtain the necessary inputs from human actors that are now participating as agents in the MAS. In mass customizing systems, this is important, because the necessary decentralization is now supported by the information system, due to fact the system's borders have actually become indistinct.

The decentralization of the production planning and control concept is also to be reflected in the implementation of the production planning and control system. It is also today that in decentralized structures central systems are used for the planning. Zelewski calls this issue the *implementation failure*. To solve this problem, a fit of the production planning and control concept with the information system and the used techniques are necessary. The use of Internet-based production environments support this fit, because Internet technologies are inherently modular and therefore the resulting information systems, in this case the production planning and control system. The actors approach allows implementing the production planning and control system as a multi-agent system, because the production system structure supports natively the necessary separation of domains for the design of software agents.

Nonetheless, mass customizers have still to cope with the problem of huge amounts of orders. These are now executed in a decentralized, modularized, and agent-based environment. In mass customization, a direct interface to the configurator is appreciated. Ideally, every order from the configurator is directly submitted into the production planning and control system, where it is scheduled immediately. This is a complex task because many orders are different and therefore require different procedures. Therefore, a production planning and control concept in mass customization should try to hold the customer order as a (abstract) unit and to route it through the necessary production steps and to exchange them between the agents. This abstract unit represents the planning and control efforts that are normally performed by the production planning and control. Therefore, the order unit has to know about the due dates and other important parameters. In our approach, we can interpret this unit as an actor that acts on behalf of the consumer. This leads the customer to become a „prosumer" (Piller/Moeslein, 2002), which means the consumer takes over actions that in mass production are executed internally. The consumer creates an order and causes the creation of an information technological actor representing the order (unit). Due to acting on behalf of the consumer, this actor takes over the role of an agent in the information system.

Several mechanisms have been developed to implement such an approach. The necessary requirement is an interaction infrastructure, that allows multiple communication and coordination relationships, which are provided in Internet based production environments. Similar approaches have been presented e.g. by the PABADIS project also for the use in mass customization (Penya/Bratoukhine/Sauter, 2003), but on the shop floor level only, where the manufactured goods are represented as autonomous software agents and machines and resources as resource agents. We concentrated on a higher, managerial level. Through this approach a close connection to the configurator occurs. This leads to a seamless integration from the order entry to the field level. Through the ideal transaction conditions in the production environment the application of software agents enlarges the responsiveness and the planning accuracy. The complexity due to the high amount of orders and variants is reduced by the distribution of decision competences to the smaller production units. They have full information about customer orders and are able to operate autonomously to fulfill their tasks.

Therefore, mass customization becomes more applicable, and support through the integration of the customer, the more efficient coordination, better allocation of resources and more accurate planning by MAS in Internet based production environments. Compromising, by combining the use of Internet-technology-based production technologies and information systems with the MAS-concept, the production planning and control in mass customizing companies can realize the benefits of MAS.

3.2 Reconfiguration of the Production System

Mass Customization is a strategy to better meet the individual needs of the customers. Those needs are relatively stable (Vriens/Hofstede, 2000), but change after a certain period of time. If the varying needs cannot be satisfied by the actual variants, new variants have to be set up. There are three possible strategies to alter the production environment:

- change/adaptation of the actors in the production system
- add new actors
- change parts or the entire production system structure

To implement those strategies, a production system requires more flexibility and adaptability of all actors, as well as capabilities to change structures. The better these abilities are, the lower the planning and design efforts are to change the structure or the actors of a production system. The changes in structure and actors should be ideally performed constantly accompanying the changes in customer needs, because the customer needs are changing not revolutionary, but steadily over the time. Therefore, it would be the best to adapt the production system steadily. Then it is possible to fulfill the customer's needs over time. Revolutionary system and actor redesign would require a shutdown of production. Especially in mass customization this is disadvantageous, because it is actually not possible to produce on stock and therefore this would cause huge selling losses. Therefore, actors in the production system have to be able to change quickly during normal operation. Additionally, due to the fast changing customer needs a new design of the technical and organizational structures have to be realized in less time and existing configurations are valid for shorter time cycles.

Therefore, the production system must be enhanced by technologies that support the management in implementing new and adapted installments. In decentralized organizations, this ability to perform this change is often called reconfigurability (Wiendahl, 2002). Additionally, the Internet based production environments enable at least partly self-adaptation of actors. Even the self-adaptation of the system structure is potentially realizable with agent technology (Wiendahl/Harms, 2002). We consider MAS in Internet-based environments as a key factor to provide adequate reconfiguration abilities in mass customization. Conventional systems are unlikely to provide the possibilities. Especially in production planning and control, these systems are not able to provide the necessary flexibility. These systems would have to be changed rather revolutionary. To compare the results of the reconfiguration, the *efforts* to modify the system and the system's components, as well as the *efficiency* of the resulting configuration must be considered (Urbani et al., 2002).

Efforts may be planning and design, but also necessary investments in reconfigurable actors and systems. To analyze efforts and efficiency of reconfiguration, we examine separately a reconfiguration of the production system and its subsystems, as well as the adaptations of actors in the production system of mass customizers.

The *change/adaptation of actors* causes the least amount of effort to meet new demands. In artificial actors this may be done by an enhancement of current abilities such as adding additional capacities or extending information technological agents with additional planning algorithms. The changes may be planned and implemented by the management, but due to the autonomy of actors in an Internet based production system it may be driven by the actors itself. The changes of actors may address some attributes or may change the whole performance of actors. In practice, adaptations e.g. in machines are directly transferred into the MAS, because the machine is automatically an agent, when it receives a work order from another actor. Changes in single actors that do not affect the general structures in the mass customization environment will not cause as much costs as a reconfiguration of the whole or parts of the system, because the other parts of the system remain the same. Through the self-adaptation abilities of the proposed information infrastructure, the changes of one actor can be attached with very low effort. The efficiency of the resulting production system is dependant upon the technical changes in the specific actor, but it is likely that the efficiency of the overall system remains the same in terms of the information or the material flow, because the decentralized agents adapt instantly to the new attributes of the changed actors.

To adapt the offered variants, additional process steps or the extension of capacities is necessary. This could be done by *adding new actors* to the production system. Because the overall production processes remain the same, only the additional features have to be integrated into the running production environment. This may occur if e.g. a furnishing customizer adds a new actor for new surface treatments. Multi-agent systems are able to integrate the new actors by adding its agent. If only the capacity is enlarged by adding a new actor (e.g. an additional machining center), the scalability of Internet-technology based systems ensures the integration without problems. Conventional FAN also support this approach, but e.g. the new machining center would not be able to act as an agent in the MAS, but would only enlarge the capacity of the master system. This would prevent decentralization efforts of an additional, autonomous actor. In this context, the latest concepts for adding new capabilities to the current production should be considered. The concepts of mobile plant (http://www.mobile-fabrik.de or also http://www.tempofak.de) try to mobilize production modules. An ongoing project in Germany tries to evaluate flexible mini-plants for use in mass customization (SFB582, 2003). These concepts allow a fast inhousing of necessary technical features for manufacturing. The modules may be viewed as actors. In our infrastructure, the mass customizers integrate the modules as actors in the production system. Those (organizational) actors participate instantly in the MAS. Adding new actors or changing existing actors often leads to a change in the production system, which means it has to already be or it is reconfigured automatically. This occurs because through the self-coordination of actors changes also the material flow. The inhousing concepts may significantly reduce the efforts of adding new actors, at the remaining efficiency.

The *change of the system structure* causes the most effort. The changes in a self-adaptive system are hard to predict, therefore potential changes in the system efficiency arise. The talk of reconfiguration, when the structure of the production environment changes. This makes it necessary to also alter the information and the material flow system, as well as the organizational structures.

Variable actors in the operation subsystem are an essential condition of flexibility. Nevertheless, the mobility and/or the variability actors were examined in the previous production research for flexibility only in relatively narrow confines. However, if companies apply Internet based Production Concepts the communications network and the interaction between actors are in the center of consideration and have a high influence on operations management. The communication network enables actors continuously to form new (bi- and multilateral) interconnections. The resulting volatile transaction networks formed between the actors in the operation subsystem enable „fluid“ structures or even interorganizational spherical networks (Miles/Snow, 1995). For example, many actual research projects aim at the development of high flexible infrastructures that enable even the spatial mobility of heavy load facilities (Mobile Produktion, 2003). These changes for operations are the basis for a reconfiguration in the production environment of mass customizers. The problem of reconfiguration is to ensure the efficiency of the new configuration. An often-discussed tool to gather the necessary information is simulation. Simulations may run on real-time data of the existing system, considering the desired changes of the analyzed domain (Baker et al., 1999, p. 65). In addition, the generation of the tested scenarios is a field for MAS. Mass Customizers can generate different scenarios by MAS, which also suggests it to be the best option (Wiendahl, 2002; Kornienko/Kornienko/Levi, 2003).

The reconfiguration in organization requires the adaptation of the information systems, as in production planning and control system, the product data management and in the interface to the configurator, because the change in the production system often changes the production possibilities. Production planning and control represents the operation subsystem is for this purpose. It follows that modifications of the operation subsystem due to Internet Technologies or Internet based Production Concepts also lead to modifications of the production planning and control. In other words: The concrete organization of an operation subsystem is important for the design of the production planning and control. The use of MAS in one of the effected information systems will reduce the altering effort, because single agents represent the changed facilities in the production system. In such an infrastructure, MAS are not encapsulated into one system, but evolve by the connection of different static agents through a number of mobile agents, where the form of communication, trading, and the transactions are standardized. This structure leads to a strong similarity of organizational and information system structure. That also permits one to simultaneously attach changes in the structure in the organization in the information system.

Structural changes cause in many industries a huge amount of effort. Therefore, companies try to hold a specific structure as long as efficiently possible. One possibility to alter the system by keeping the structure constant is to reconfigure the material flow system. For example, autonomous driverless robots are an example that allows more flexibility and also efficiency in the production system, without changing the structure. In mass customization these robots can support the material/part flow in the variant production, if it is not possible to implement conveyors or new circumstances such as additional variants making those systems insufficient.

Through the combination with the information system, it is possible to determine the state of the materials flow system at any time. This information can be used then in the entire production system in real time. This permits a redesigning of the flow of materials system itself. The entire layout of the carrying out system becomes with that much more flexible, because the materials flow system to the individual machines and plants can be arranged, without losing efficiency in this case.

There are also far-reaching approaches that analyze the use of MAS in structural changes. Wiendahl et al. (2001) analyzed how self-organized structure adaptation may work. They also considered Internet-technologies as a necessary condition for implementation. For mass customization, it is questionable that MAS lowers effort, because the necessary knowledge that the agents need is huge and therefore there has to be a large amount of effort to implement that. Although there are borders for agent-based reconfiguration in mass customization, we can state that the possibilities are much higher compared to other, conventional information system approaches.

3.3 Enabling Mass Customization?

The enhancements in the production planning and control and reconfigurability of the production system support the mass customization strategy. Due to the possible alignment and the fit of internal structures, we have to analyze the overall usability of the approach for mass customization. Reiss (1998) presented an approach for evaluating the interdependencies of information systems and managerial concepts. He differentiates two main impacts, being the empowerment and the enabling. Empowerment occurs, if the managerial concept induces the development/application of new information systems/information technologies. “Enabling”, means that an infrastructure allows or supports implementing business strategies or concepts. Mass customization is built up on the possibilities of modern information technologies. It induces the development of special technologies or the introduction of new information systems. Mass customization has to be introduced gradually by adding several abilities to the production environment and requires adequate infrastructure in the production environment. The implementation of MAS in Internet based production environments has several positive influences on the applicability of mass customization strategies. Therefore, it is conceivable, that the application of this infrastructure leads to an overall better applicability of mass customization. Mass customization is not an „as-it-is" concept, but has to be tailored and developed. Every company up to now needed time to synchronize a balance between the actors and sub-systems in the production environment if they set up mass customization (Piller, 2002). A more serious challenge is to hold the mass customization position. An enabling infrastructure has therefore to offer prerequisites for sustained realization of mass customization. We have now to analyze, if MAS in Internet based production environments lead to an enabling of mass customization.

- Dynamic manufacturing requirements

  The random customer orders and the small batch sizes of the orders are a serious problem for mass customizers. Especially through the use of MAS, mass customizers can handle the complexity at good response times.

- Flexible resources

  Mass customizers need certain amounts of multiple capabilities at most of the manufacturing resources (workers, robots, machine, workstations, etc.) in order to provide the demanded variants. The flexibility of resources lead to the ability that the same job can be carried out on different machines or assembly workstations. The actors view on production allows one to exactly specify the capability of resources and even to identify potentials for mass customization.

- Postponement of product variety

  The enhanced communication and coordination abilities in the production system also allow enhancing batch sizes and achieving economies of scale. This is because the flexible resources and the MAS-based control allow the implementing of a continuous production also temporarily.

- Product family architecture

  Products are designed with concepts of product family architecture (PFA), which is to be considered at the design or the reconfiguration of the production system.

- Flexible process routing

  The mass customized products often involve modular design, non-linear process plans, alternative routings and variable sequences relax constraints in traditional routing. MAS in Internet-based environments, permit more freedom in routing and to find optimal routes. Through an adaptive material flow system and the multiple abilities of actors, the production system can significantly increase flexibility of process routing.

Compromising, the presented features of MAS in Internet-based environments enlarge the applicability of mass customization. Several problems in mass customization manufacturing can be solved. Therefore, we consider the proposed approach as an enabling infrastructure for mass customization. This means the new technological and organizational principles support the adoption of mass customization.

4 Constraints and Requirements

A successful implementation of MAS in Internet-based environment depends on the application of the suitability of information technology, information systems, as well as the organization. There are several barriers that need to be overcome by applying the suggested organizational structure, the necessary information systems, as well as the prerequisites for the application of MAS.

First of all, the discussed decentralization is to be realized effectively. Additionally, the actors approach requires a modularization of the organization. Management has to hand over competencies to other actors. There are several problems to consider. First of all, the actors must be able to cope with the additional (leading-)tasks they have to fulfill. Therefore, human actors have to be trained well, to handle the responsibility and the coordination tasks that have to be done autonomously. What is important is the embedding of artificial actors into the organization. The consideration of organizational actors is an additional issue. The problem of different modularization concepts is a lack of explicit interfaces between the different organizational units. Organizational actors allow the considering of e.g. a work cell as a unit. Based on this, it is possible to define clearly the in and outputs of such an organizational actor. This is necessary to allow an efficient interaction with artificial actors.

From a human resources perspective, management, as well as employees must be prepared for working in this suggested environment. They have to be able to understand what artificial actors are and what they are able to do. Artificial agents in an Internet based production environment differ from previous approaches, because they are acting closer with human agents. This means, MAS are no longer an nontransparent black box in a remote information system. They are now a part of the organization, because they are participating directly in different processes. Thus, it is necessary to explicitly define the actors and their attributes. The definition of actors also supports decentralization, because the decision rights of the actors are defined.

Technological barriers are also critical. Internet based production concepts require adequate machinery that has embedded computation power. In addition, there has to be the necessary networking infrastructure. Additionally, barriers result from the existing infrastructure. In many cases, industrial firms have to protect their existing investments, so they have to continue in using a technologically obsolete infrastructure. Furthermore, in some cases, the application of specialized, non IP-based machinery is necessary and/or the cost of a complete migration to Internet based field area networks a prohibitive high. Companies can solve this problem with gateways between the field busses and the Internet Technologies or the application of convergent infrastructures. Big suppliers in the field of the automation technology offer already corresponding solutions or even Internet-suitable fieldbus-systems such as ProfiNet.

Two fundamental problems in information technology are optimal implementation and security. While the original implementation problems of Internet technologies and their implementation in production processes are well known, security aspects are the main obstacles and barriers to industrial applicability. Although security aspects are not considered in many cases by the implementation of Internet based field area networks, there is a main risk that important machines and plants are exposed to different attacks, e.g. by hackers, viruses and trojans. These problems arise especially when customers and suppliers connect their systems to the new infrastructure on the shop floor directly, e.g. in mass customization. However, technical and/or organizational protection mechanisms already known reduce the problems, e.g. cryptography, virus scanner, firewalls, and access controls.

An internet based infrastructure and the adequate organization structure given; MAS may be integrated in the production environment. There are many concepts that have developed mechanisms for the coordination and the problem decomposition in MAS. These approaches do not plan out the implementation, but concentrate on the conceptual draft of the necessary mechanisms and the separation of different agents. Other approaches try to implement these mechanisms experimentally. Except the Pabadis approach, there are no projects that are trying to use MAS in actual environments. Therefore, there is a barrier for application because ambitious companies would have to engage in research projects to implement MAS. The presented approach allows the introduction of the MAS approach systematically. This means that especially dispositive actors in the production environment may be replaced through information technology or that machines will be extended with actors capabilities a now may be represented by an agent.

For the application of multi-agent systems, there are mechanisms needed to locate actors and their attributes in the production system. The directory of resources is a promising concept to link the information stored in the various information systems to the organization and therefore make it applicable. In fact, this concept is a management tool to cope with complex organizations broadly supported by information systems. A rudimentary version is the DNS (Domain Name system) of the Internet, which matches domain names to the IP-addresses worldwide. A more complex standard for that is UDDI (Universal Directory Description Interface), which is actually a part of the intensively discussed Web-Services. Apart from the technical concepts, the idea of the directory approaches is to link the information within a system (e.g. production system) to the various resources within the system. The directory stores the attributes of every actor within a system and represents its attributes. The directory enables the actors of the concerned system to find and interact with all of the other actors. The Internet-technology based approach allows a universal directory for the entire system, which was prohibited thus far by the technological barriers. The directory also contains the information necessary to set up information transfers and determines which information an actor can provide.

5 Conclusion

Compromising the application of multi-agent systems (MAS) in an Internet based environment has several positive effects that lead to an enabling of mass customization. The necessity reaching conformity between information systems and the organization structure are indispensable for mass customization companies. Especially information systems are often not aligned with the organization structure. MAS are a promising concept that provides the necessary flexibility and changeability in decentralized environments. Actual MAS-approaches in mass customization neglect implementation considerations such as the integration within the information infrastructure and the uniformity to the organization.

Internet based production concepts offer a solution to the application failure of multi-agent systems, if an actor based view on the production systems is employed. Actors are human, artificial (mechanical or information technological) and organizational units that are autonomous, persistent and communicative. This approach allows a conceptual integration of MAS into the production system by considering agents as actors that act on behalf of other actors. The actor approach permits the adoption of the theoretical benefits of MAS into the mass customizing manufacturing system. The application of Internet based production concepts provide the necessary decentralized organization structure, as well as technical prerequisites.

The presented approach leads, as compared to conventional mass customization manufacturing systems, to a more flexible, quickly responding production planning and control. The decentralization and the autonomy of actors allow fast and comprehensive reconfiguration of the production system by applying the artificial intelligence of MAS. Mass customization profits by those changes through time benefits and economics of scope.

The problems reside in the adoption by management and employees, a multitude of technical issues, as well as security concerns. Future research will have to clarify whether the used criteria to test the applicability or an enabling of mass customization are valid and if the presented approach is a suitable basis for dedicated mass customization manufacturing.

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