Structured Information Processing as Enabler of Versatile, Flexible Manufacturing Concepts

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Abstract. Automotive production systems face the challenge to produce models and brands with different drive concepts and individually configured equipment variants in a highly efficient way.

Studies on modular assembly systems in automotive industry have demonstrated potential for productivity gains through the implementation of an alternative, value-add-oriented process organization. The rigid concatenation of mechanical production processes is the limiting factor; firstly, for an efficient implementation of product individualization and secondly, for a highly available robust production which can optimize the overall factory production flow.

Rising degrees of freedom in material flow control associated with more flexible production flow increases the complexity of the overall production system. Decision support for humans by planning systems with integrated control logic is thus a decisive factor for mastering complexity. Currently, the overall performance of modular manufacturing processes is not sufficiently supported by the IT-architecture on factory level. The individually operating subsystems are not capable of supporting reactive manufacturing control.

As a basis for reactive manufacturing control, the information requirements towards modular manufacturing processes across different domains are defined in this paper. Furthermore, a cross-system information and communication matrix is proposed that structures information processing between individually operating subsystems. The application of broker-technology could subsequently enable holistic information-based control on factory level to support human experience-based decision making.

1 Introduction

The development of technology markets, especially in the field of digital data processing, is taking place faster than in almost all other areas and offers new possibilities for

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the demand-oriented control of production processes [1]. There is potential for optimization on the shop floor through the occurrence of unforeseen, short-term changes that require a high degree of coordination and control [2]. The technical possibilities of digital, flexible IT-networks offer great potential for increasing productivity for medium-sized businesses and industry. One potential of the increasing connectivity in production systems is the possibility of implementing alternative, modular manufacturing concepts. The challenge for automation technology is to support the process requirements for flexibility and autonomy in the production systems with comprehensive information and control technology [3].

In the following, a procedure will be presented which shows the corresponding information requirements and possibilities for interaction in modular production systems enabled by agent-based control systems.

2 State of the Art and Related Work

In the following section, the influence of alternative manufacturing concepts for the automotive industry is given as well as the development of Cyber Physical Production Systems (CPPS) and the associated challenge for the implementation of control concepts in production systems.

2.1 Efforts Towards Implementing Alternative Manufacturing Concepts for Modern Production Systems in the Automotive Industry

Current manufacturing systems in the automotive industry are based on the concept of continuous flow production for manufacturing tasks with a high proportion of identical parts and a uniform, high production volume [4]. With the implementation of product individualization in mixed model lines, the line concept is being questioned to be the most effective and efficient manufacturing concept. As a result of the wide range of variants, the production system has to support different process variants and thus a wide range of flexibility requirements are addressed with alternative methods [5, 6]. A freely interlinked material flow can meet the requirements for flexibility and dynamics in the production system and, among other things, increase the value-add time per resource as a whole [7].

In order to cope with the flexibility requirements in mass production, a change in the manufacturing concept with modular stations based on the model of decentralized fractals can be considered, which, by using intelligent technologies, can make the considerations on the organizational principles realizable [8]. For this purpose, design principles were developed which can support humans in the form of rule-based planning for a modular assembly concept in variant flow production [5, 9].

With the intended paradigm shift to an Industry 4.0 age, the complex cognitive work content for humans has increased [2]. A modular production system with an increased number of degrees of freedom requires intelligent software support to solve complex production problems.

2.2 Distributed Information Processing as Requirement for Implementing Modular Production Systems

Due to the leaps in development in the field of information and communication technology, electronic hardware components with intelligent software can be organized as Cyber-Physical Systems (CPS) or Cyber-Physical Production Modules (CPPM) in a Cyber-Physical Production System (CPPS). Industrie 4.0 components describe a physical object that provides a digital and actively communicating representation over its product life cycle – the asset administration shell (AAS) [10]. By means of an actively communicating representation of the actors in a CPPS, a self-organized, value creation-oriented coordination of production process steps and production resources is possible [11].

The state-of-the-art of control systems in automotive industry is a predominantly heterogeneous, historically grown system landscape according to ISA95. However, systems with several independent decisions that are distributed over time offer potential for agent-based control systems [12]. A dynamic reconfiguration with the consideration of information from several process participants requires, for example, parallel, decentralized and autonomous decision-making processes, which must be enabled by the control architecture. An agent-based control system can be used to integrate cyber physical systems into production systems [13]. Control architectures using middleware technology seem promising for providing cross-system communication and information integration for subsequent physical and logical reconfigurability in the system [14].

Approaches to the use of multi-agent systems (MAS) in production control rely on data from existing ERP-, MES- or SCADA-systems to integrate level-specific information [3, 13–15]. One method for developing control systems for MAS is the Designing Agent-based Control Systems (DACS) method, which is a suitable method for solving control problems in production based on shop floor decisions [13]. It designs agents based on decision clusters and interaction of the entities and their information flow. It is easy to apply in different domains and was extended by Vogel-Heuser et al. to include the possibility of integrating the field level [13].

Although there are several approaches for designing MAS in industrial use cases, implementing existing methods with the latest technology in both research and industry is missing. Existing approaches do not fit modern Industrie 4.0 standards such as RAMI 4.0, which leads to a limited deployment of such system, even if they have reached an industrial degree of maturity. There is a gap in the current industrial information structures for supporting reactive manufacturing control. Therefore the potential of modular processes in manfucaturing systems is still limited. The holistic consideration of distributed information from different systems needs to be supported by the information design of the manufacturing system.

3 Concept for Information Processing in Alternative Versatile Manufacturing Systems Implementation

In today's production systems in the automotive industry, humans are responsible for cross-divisional information processing. Information systems support them in the processing of planning and control tasks, but humans link the information to form an overall picture based on experience. A future system structure for modular production systems is required, which allows the user to combine the distributed experience-based process knowledge and make it available in the system in a sustainable way. This will allow decisions spanning different systems and areas to be made in an optimal way in the future. The following procedure is proposed for an application of a method for agent-based control of a modular manufacturing system:

1. analysis of the design principles [5, 9] in 3.1 regarding the information requirements for modular manufacturing systems and a resulting
2. definition of information requirements for modular production in the end of 3.1
3. informational relationships of level-specific interaction of process components in 3.2

3.1 Requirements for Information Processing in Modular Production Systems

The manufacturing system with a modular structure is intended to enable a flexible allocation of production resources and production process sequences. Depending on the order situation and the planned production program, this can lead to a need for negotiations between the actors in the system. Therefore, a planning methodology for demand-oriented design and a corresponding condition-based control is required. The previous principles according to Kern et. al [5, 9] are structured as follows: In the first step, the basic relationships between product and process are presented, in the second step, the requirements for a dynamic system network and in the third step, the extensions for the production system through the influences of the areas of quality, logistics and adaptations in the system are added.

A) Basic product and process information support: For a **variable station sequence**, the product-specific priority graph must be taken into account. This graph organizes the predecessor and successor relationships of the shoring process and determines the degree of freedom of the sequence. The workstation requires the ability to identify products and the ability to execute the required process steps. The station represents itself and its process capabilities determined by its resources and employees and is a production resource for the processing steps. On the other hand, the product provides the information about the **product-specific processing requirements** and process steps still to be completed. For the lead time of the product in the stations, no cycle-time-bound time specification applies, but rather the process time. The product and the station require a **self-description and identification capability**.

B) Dynamic system network: In a network of several workstations and products, status-based self-control and demand-dependent allocation of the stations is required as a logical component. The central assignment of products to process stations represents a recurring negotiation situation depending on the number of variants and production sequence. Optimum central process control can only be achieved by coordinating decentralized product needs and a central process control instance. The information about product sequence, product processing time and station availability in the status current priority graph must be transparent and available in “real-time”. The reactions due to capacity and demand changes should be dynamic and flexible. One example is the higher-layer reaction to changes in customer demand and the related product mix in the production plan, as well as the lower-layer reaction to short-term disruptions in machine scheduling planning. This requirement for **logical reconfigurability** can be achieved by **real-time data exchange**.

C) Extension of the system behavior (integration of further control loops).
Integration of Logistics: The challenge of multi-model lines is to organize logistics expenditure in line with demand. A demand-oriented provision of components at the installation site requires real-time communication with the Automated Guided Vehicle's (AGV) central control system and the warehouse system. AGVs must be able to react locally to **safety-relevant external influences in real time**.
Integration of Quality: The modularization of the production process and the associated possibility of parallel processing of the same or similar materials at different locations requires the **flexible integration of quality control loops**. A comprehensive traceability of the individual and distributed shoring processes is necessary. For this purpose, the possibility of central storage of decentralized process results must be created. Evaluations in real time enable centralized knowledge for process optimization. Central coordination of decentralized quality information could even contribute to **predicted process and quality improvement** by appropriate use of technology.
Integration of Resource (CPPM/employee): The information about decentralized change or integration requirements of CPPM or employees is taken into account by the central process monitoring system and processed according to the production program. Components or entire stations can be temporarily blocked by setup processes or qualification measures and then be made available again in modified form. They require an adjustment of the capacity planning in the overall system for product, process, logistics and quality. In addition to the already mentioned logical reconfigurability, this also requires the ability of the system to consider **physical reconfigurability**.

Table 1 presents an overview of the requirements for decentralized (station-related) and centralized (network-related) control loops in the four information structure clusters. This serves, first of all, for rough planning and sets the premises to be observed for further detailed planning of the systems and information interactions.

3.2 Structuring of the Information Flow of Entities

Based on the material flow relationships, an overview of the interaction of all process participants in the production flow can be displayed. The aim is to derive the information relationships between the process participants from the process sequences of the freely linked material flow. In this way, the individual information relationships for the variant to be produced can be structured to show control decisions. This procedure makes it possible to integrate the requirements identified in step 3.1 into an interaction representation of the material and information flow. Figure 1 shows an example of centralized, decentralized and hybrid control structures in an interface matrix. By pointing out the process driven relationships for the levels of the production system, it can be shown which information-technical relationships exist between the actors of the respective level.

From Fig. 1, the level-specific control requirements can be derived and clustered with the interdependent information relationships. By applying the interface matrix,

Table 1. Information requirements for holistic production systems

Information Requirements of Modular Production Systems	Product		Process		Logistics		Quality	
	Central	Decentral	Central	Decentral	Central	Decentral	Central	Decentral
Self-descriptiveness	–	x	–	x	–	x	–	x
Identifiability	–	x	–	x	–	x	–	x
Real-Time Capability	x	x	x	x	x	x	x	x
Logical Reconfigurability	x	–	x	–	x	-	x	-
Physical Reconfigurability	x	x	x	x	x	x	x	x
Safety	–	x	-	x	–	x	x	x

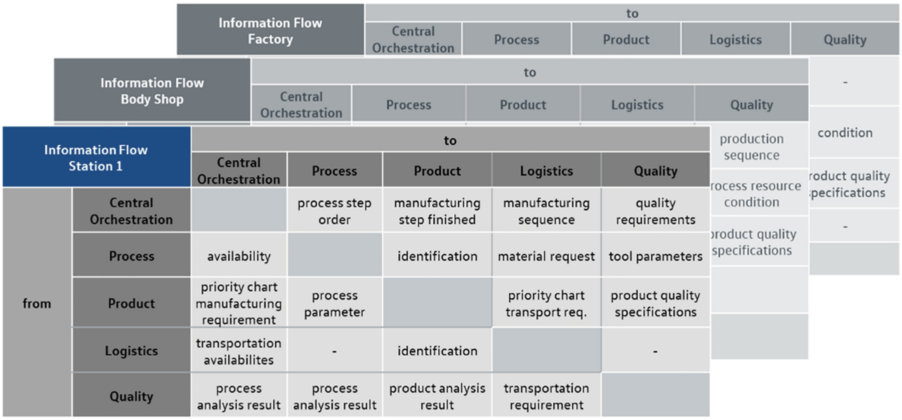

Fig. 1. Interface Matrix for the material flow driven interaction of entities and their information flow on system and station level

the information flow relationships of the actors and the central (horizontal and vertical connections) or decentral (diagonal connections) control needs become transparent. This can be used as a basis for designing control loops processing the relevant product, process, quality and logistics information for each level. After the basics for the product- and process-related design of modular assembly systems have been described, a holistic information support is required. The integration and consideration of the individual cross-process information of the corresponding process participants and other areas becomes challenging. Therefore, domain spanning MAS and intelligent middleware solutions can support handling this complexity. The interface matrix is also suitable for the analysis of existing processes which can be transferred into a modular structure.

4 Discussion and Conclusion

With the analysis of the design principles and the derivation of information requirements for modular assembly systems, a step towards a cross-system control for an application in modular production systems in the automotive industry has been taken. In interaction with the application of the interface matrix, the process participants can be identified and integrated according to their process requirements. The control requirements of modular assembly systems fulfill the factors for the agentification of control systems and the development of a distributed, agent-based control system therefore offers potential for further application.

With these decision clusters, the design for processing process, product, logistics and quality information can be pursued further, which enables an agent-based design for nested control loops in production systems. The computing effort in decentralized or centralized system structures for ensuring a robust and efficient operating system behavior must then also be taken into account. As no production systems with a modular structure have been operated in automotive industry so far, the described way of designing the information technology support with a cross-system approach will also be validated towards relevant KPIs.

In this article, the information flow requirements for modular assembly systems were defined and a novel procedure for structuring information relationships could be proposed. It is based on the product- and process-related manufacturing requirements and takes into account the information relationships with logistics and quality. By applying the procedure for structuring information relationships and considering the information requirements, flexible, dynamic production systems can be reconfigurable in terms of information technology. Further work will quantitatively validate the procedure and investigate the integration of further external system information using latest middleware architecture technology like OPC-UA, Apache Kafka, and BaSyx. The results can then be transferred into a sustainable system structure connecting different domains in order to deliver the informational basis to implement different manufacturing concepts in the automotive industry. Subsequently a strategy to design the information processing for central and decentral processing can follow in further research by using methods from the field of systems theory and engineering.

This seems to be a promising approach for the implementation of cross-system optima linking different abstraction layers by using latest technology. The aim is to deliver a broadly applicable system structure based on structured information processing of product, process, logistics and quality information for efficient and intelligent manufacturing systems.

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