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Autonomy in production logistics: Identification, characterisation and application

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Abstract

Competitive enterprises have to react fast and flexible to an increasing dynamic environment. To achieve the ability to adapt on these new requirements autonomous cooperating logistic processes seem to be an appropriate method. In order to prove in which case autonomously controlled processes are more advantageous than conventionally managed processes, it is essential to specify what is exactly meant with autonomous control, how autonomous control does differ from conventional control and how the achievement of logistic objectives in autonomously controlled systems can be estimated and compared to the achievement of objectives in conventionally controlled systems. This paper introduces a general definition of autonomous control as well as a definition in the context of engineering science and its meaning in a logistics context. Based on this, a catalogue of criteria is developed to ensure the identification of autonomous cooperating processes in logistic systems and its distinction to conventionally controlled processes. To demonstrate this catalogue, its criteria and the concerning properties are explained by means of an exemplary shop-floor scenario.

Keywords: Autonomous control; Logistics; Production systems; Production planning and control

1. Initial situation and call for action

Over the past years, an increase in structural and dynamic complexity of production and logistics systems could be observed. This development is caused by diverse changes, for example, short product life cycles as well as a decreasing number of lots with a simultaneously rising number of product variants and higher product complexity [1]. As a result, new demands were placed on competitive companies, which cannot be fulfilled with conventional controlling methods. Conventional production systems are characterised by central planning and controlling processes, which do not allow fast and flexible adaptation to changing environmental influences. Establishing autonomous cooperating logistics processes seems to be an appropriate method to meet these requirements. The idea of autonomous cooperating logistic processes is to develop decentralised and heterarchical planning and controlling methods in contrast to existing central and hierarchical aligned planning and controlling approaches [2]. Autonomous decision functions are shifted to logistic objects. In the context of autonomous control logistic objects are defined as material items (e.g. part, machine, conveyor) or immaterial items (e.g. production order) of a networked logistic system, which have the ability to interact with other logistic objects of the considered system. Autonomous logistic objects are able to act independently according to their own objectives and to navigate through the production network themselves. The autonomy of logistic objects is possible since recent developments by information and communication technologies (ICT), for example radio frequency identification (RFID) for identifying, global positioning system (GPS) for locating or universal mobile telecommunications system (UMTS) for communicating of logistic objects [3].

These new approaches are currently investigated within the Collaborative Research Center ‘‘Autonomous Logistic Processes—A Paradigm Shift and its Limitations’’ at the University of Bremen, which deals with the implementation of autonomous control as a new paradigm for logistic processes [4]. The intention of this paper is to

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explain what is meant by autonomous control and to show potentials in logistic systems, particularly in production systems.

Therefore, a definition of the term autonomous control is given. Based on the main statement of this definition, a catalogue of criteria is developed in order to identify autonomous cooperating logistic processes and to emphasise how conventionally managed and autonomous logistics processes differ. The criteria and its individual properties are explained on a concrete object of investigation by a scenario of a manufacturing system. In conclusion further research activities concerning evaluation of autonomous control are presented.

2. Definition of autonomous control

The vision of autonomous cooperating logistics processes emphasizes the transfer of qualified capabilities on logistic objects as explained above. According to the system theory, there is a shift of capabilities from the total system to its system elements [5]. By using new technologies and methods, logistic objects are enabled to render decisions by themselves in a complex and dynamically changing environment. Based on the first results of the work in the context of the Collaborative Research Centre (CRC) 637 "Autonomous Cooperating Logistic Processes—A Paradigm Shift and its Limitations" at the University of Bremen [6], autonomous control can be defined as follows:

> Autonomous Control describes processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently.
>
> The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity. [7]

Based on this global definition of the term autonomous control a definition in the context of engineering science was developed, which is focussed on the main tasks of logistic objects in autonomously controlled logistics systems:

> Autonomous control in logistics systems is characterised by the ability of logistic objects to process information, to render and to execute decisions on their own.

For a better understanding, the main statements of the given definitions of autonomous control such as decentralized decision-making in heterarchical systems, system elements ability of interaction as well as non-deterministic system and positive emergence, are described and discussed below.

2.1. Decentralised decision-making in heterarchical systems

One feature of autonomous control is the capability of system elements to render decisions independently. Autonomy regarding decision-making is enabled by the alignment of the system elements in the form of a heterarchical organisational structure [8]. Therefore, decentralisation of the decision-making process from the total system to the individual system elements is a typical criterion of autonomous control. Each system element represents a decision unit, which is equipped with decision-making competence according to the current task [9]. Due to the fact that decision-making processes are purposeful, according to the decision theory, each system element in an autonomously controlled system is characterised by target-oriented behaviour. Global objectives, for example, provided by the corporate management, can be modified independently by the system elements in compliance with its own prioritisation. For example, the objective of high due-date punctuality can be replaced in favour of high machine utilization by the machine itself. Thus, the objective system of single elements is dynamic because of its ability to modify objects prioritisation over time, i.e. during the production process.

2.2. System element's ability of interaction

Decentralised decision-making processes require the availability of relevant information for the system elements. Consequently, the capability of system elements to interact with others is a mandatory condition and thus one constitutive characteristic of autonomous control. The ability of interaction can accomplish different values depending on the level of autonomous control. The allocation of data, that other autonomous logistic objects can access, represents a low level of autonomous control. Communication, i.e. bi-directional data exchange between autonomous logistic objects, and coordination, that means the ability of autonomous logistic objects to cooperate and coordinate activities of other objects, stands for a higher level of autonomous control.

2.3. Non-deterministic system behaviour and positive emergence

In accordance with the above-mentioned definition, the main objective of autonomous control is the achievement of increased robustness and positive emergence of the total system due to a distributed and flexible coping with dynamics and complexity. Non-determinism means that despite precise measurement of the system status and knowledge about all influencing variables of the system, no forecast of the system status can be made. Knowledge of all single steps between primary status and following status is not adequate enough to describe the transformation completely [10]. Thus, a fundamental criterion of autonomous control is that for same input of initial values, there

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are different possibilities for transition in a following status. As already explained, decentralisation of decision-making processes to the system elements leads to a higher flexibility of the total system, because of the ability to react immediately to unforeseeable, dynamic influencing variables. In this way, autonomous control can lead to a higher robustness of the overall logistic system. Furthermore, positive emergence is the main objective of autonomous control. Emergence stands for development of new structures or characteristics by concurrence of simple elements in a complex system. Positive emergence means that the concurrence of single elements leads to a better achievement of objectives of the total system than it is explicable by considering the behaviour of every single system element. That means related to the context of autonomous cooperating logistic processes, that autonomous control of individual logistic objects (e.g. machines, parts, orders) enables a better achievement of objectives of the total system than can be explained by consideration of the decentralised achievement of objectives (e.g. higher rate of on-time delivery, lower delivery times) of every single logistic object.

3. Derivation of a catalogue of criteria

The identification of autonomous cooperating logistic objects requires a dissociation from conventionally managed logistic objects. The definition of autonomous control explained in the preceding chapter describes the maximum level of imaginable autonomous control. Thus, all system elements in an absolutely autonomous controlled system are able to interact with other system elements and to render decisions on the basis of an own, decentralised target system. In general, logistics systems probable contain both conventionally managed and autonomously controlled elements and sub-systems, respectively. Furthermore, it is assumed that there are different levels of autonomous control, which is called level of autonomous control. For example, one part of a production lot could be able to coordinate each production stage of the lot which represents a high level of autonomy, meanwhile other parts only allocate data regarding their processing states. Consequently, the latter mentioned case shows a lower level of autonomy.

Based on the definition of autonomous control in the context of engineering science its main characteristics are the ability of logistic objects to process information and to render and execute decisions. Each characteristic can be assigned to different layers of work in an enterprise. In accordance with Ropohl [11], different layers of work can be classified in organisation and management, informatics methods and I&C technologies as well as in flow of material and logistics, each concerning decision, information and execution system. Fig. 1 presents the assignment of the characteristics to the system layers, illustrates their correlations and introduces the main criteria of autonomous control.

The decision system is characterised by the decision-making ability. As mentioned before in autonomous controlled production systems decision functions are shifted to logistic objects, which are aligned in a heterarchical organisational structure. These functions contain planning and control tasks and enable logistic objects to assign their progression. The decision-making

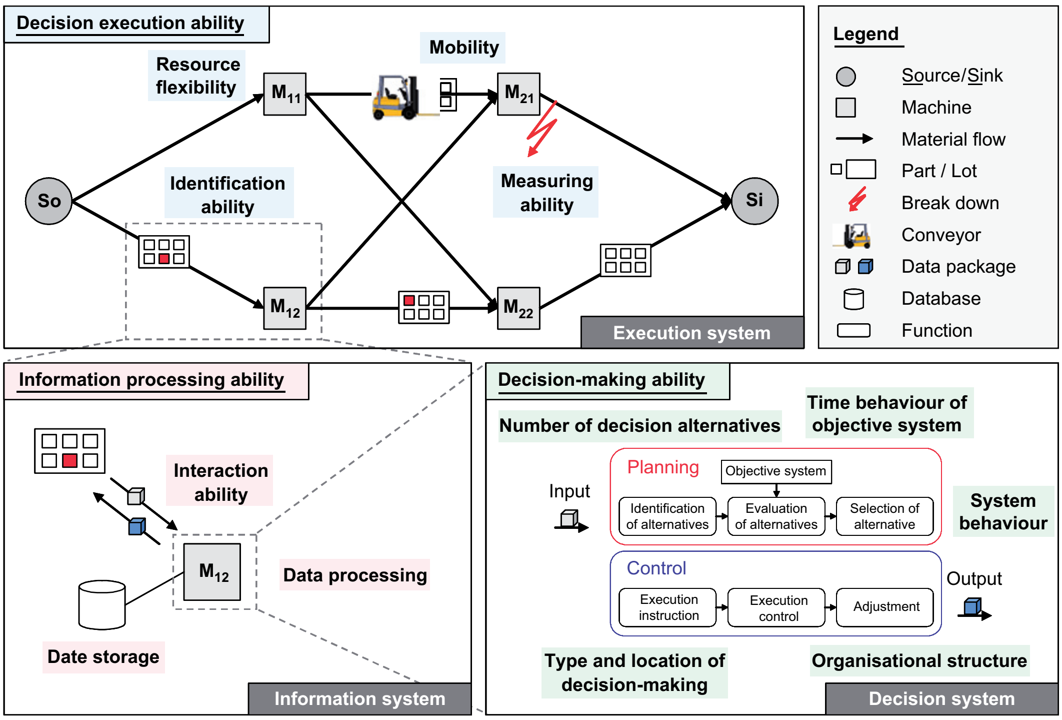

Fig. 1. System layers and criteria of autonomous control.

process includes the identification and evaluation of decision alternatives on the basis of an own, decentralised objective system, the selection, instruction and control of the best rated alternative as well as possibly adjustments.

The basis for decision-making is the information processing ability on the information system layer. In autonomous controlled production systems logistic objects must be able to interact with each other as well as to store and to process data.

The execution system layer is characterised by the decision execution ability of logistic objects. Autonomous logistic objects are able to measure their current state and react flexible to unforeseeable, dynamic influencing variables. Mobility and high flexibility of the resources are other main criteria of autonomous control in production systems.

In the following a catalogue of criteria is derived, that contains the main criteria of autonomous control described above as well as its properties, which describe the different levels of autonomous control. The catalogue of criteria is illustrated in form of a morphologic scheme in Fig. 2.

The vision of autonomous control encloses transferring qualified capabilities (e.g. decision-making, data processing, measuring) from the total system to the system elements, i.e. autonomous logistic objects. So the visualised system layers relate both to the total system and the system elements. Each criterion has a series of properties, with an increasing level of autonomous control in their order from left to right. For example, a logistic system with decentralised decision-making by its elements has a higher level of autonomous control than a system rendering centralised decisions. Grey marked properties show exemplary, how a considered production system could be represented in the catalogue of criteria. Based on this, an exemplary scenario with the individual criteria and their marked properties are described in the following.

4. Application of the catalogue of criteria

In this Section, criteria and properties explained above are described using a production logistics scenario. Fig. 3 gives an overview of a scenario of a two-stage job-shop production. Each criterion characterises the behaviour of logistic objects and is assigned to different system layer, i.e. decision-making system, information system and execution system.

The first production stage contains the manufacturing of a part on two alternative machines (M_{ij}). The raw materials

System layer	Criteria	Properties			
Decision system	Time behaviour of objective system	static	mostly static	mostly dynamic	dynamic
	Organisational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical
	Number of alternative decisions	none	some	many	unlimited
	Type of decision making	static	rule-based		learning
	Location of decision making	system layer	subsystem layer		system-element layer
	System behaviour	elements and system deterministic	elements non-/ system deterministic	system non-/ elements deterministic	elements and system non-deterministic
Information system	Location of data storage	central	mostly central	mostly decentralised	decentralised
	Location of data processing	central	mostly central	mostly decentralised	decentralised
	Interaction ability	none	data allocation	communication	coordination
Execution system	Resource flexibility	inflexible	less flexible	flexible	highly flexible
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable
	Measuring ability	none	others	self	self and others
	Mobility	immobile	less mobile	mobile	highly mobile

increasing level of autonomous control →

Fig. 2. Extract of catalogue of criteria for autonomously controlled systems.

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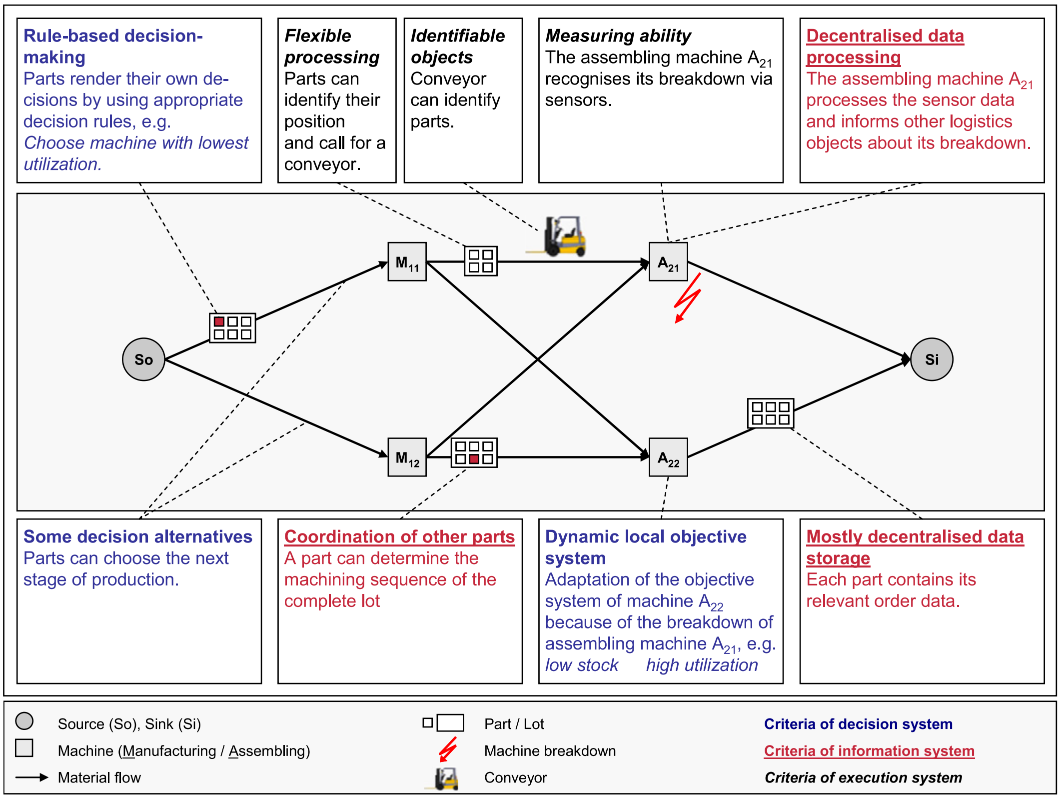

Fig. 3. Autonomously controlled production logistics scenario.

that are needed for production are provided by the source (So). In the second production stage, the assembly of the parts that were produced in the first stage is done alternatively on two machines (A_{ij}). The manufactured items leave the material flow net at the sink (Si). At a predetermined time a disturbance occurs in the form of a breakdown of machine A_{21}. In conventionally controlled production systems a machine breakdown at night would cause at least a delay of many hours before recognising the disturbance and adjusting the production plan in the traditional way.

The autonomous control of the machines provides the opportunity to react fast and flexible to disturbances. Machine A_{21} recognises autonomously its breakdown by permanent measuring and processing of sensors data. Deviations of sensors data are identified, analysed and appropriate activities are initiated. In this scenario, the machine A_{21} immediately informs other logistic objects about its breakdown, especially machine A_{22}. Based on this information, machine A_{22} could adapt its dynamic local objective system by prioritising the objective *high utilization* instead of *low stock* to counteract the bottleneck of the assembly stage. Parts waiting in front of machine A_{21} are informed about the machine breakdown. Because of this information and their measuring ability, parts can define their position and initiate their own transport to the alternative machine A_{22}. Because of the identification ability, the conveyor is able to precisely identify the parts.

The existence of alternative manufacturing and assembling stages as well as the availability of local information allows parts to render decisions regarding their way through the production process. The decision-making process in this scenario is rule-based, i.e. logistic objects act according to defined rules. For example, a part could choose the manufacturing machine on the basis of the rule "select machine with lowest rate of utilization". However in this scenario, parts are characterised by different levels of autonomous control. Some parts just have the ability to allocate data; other parts acting for the entire lot are able to navigate through the production process.

On the basis of this exemplary scenario it has been shown that each logistic system can be classified according to the level of autonomy by means of the introduced catalogue of criteria.

5. Conclusions and further research

This paper introduced a definition of autonomous cooperating processes and its implementation in logistic systems. Based on this definition, a catalogue of criteria was developed and applied exemplary on a job-shop scenario. As shown in the scenario, establishing autonomous control seems to be an appropriate method to cope with increasing complexity and dynamic environments of today's logistic systems. In confirmation of this future research has to deal with the development of a new

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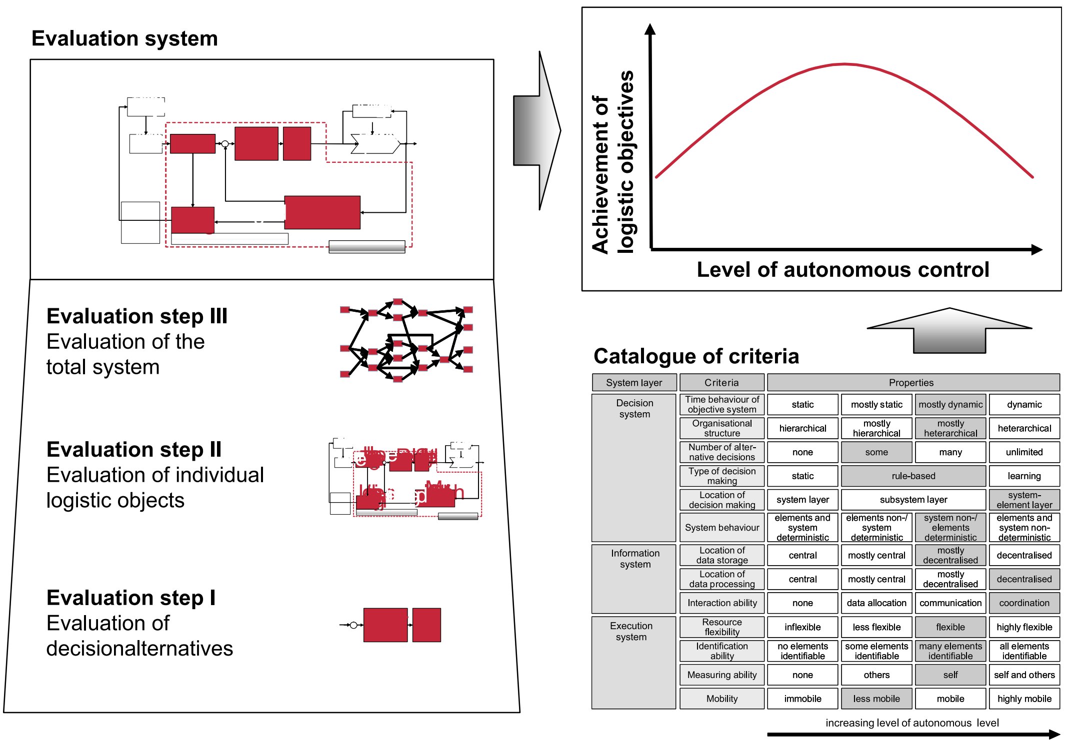

Fig. 4. Achievement of logistic objectives vs. level of autonomous control.

evaluation system to estimate the achievement of logistic objectives in autonomously controlled logistics systems. The evaluation system represents the degree of achievement of logistic objectives related to the level of autonomous control. Therefore, both the degree of the achievement of logistic objectives and the level of autonomous control must be measurable. Based on the catalogue of criteria the level of autonomous control of logistics systems can be determined with an adequate operationalisation. Furthermore, the achievement of logistic objectives can be ascertained through comparison of target and actual logistic performance figures related to the objectives low work in process, high utilisation, low throughput time and high due-date punctuality. The evaluation system consists of three evaluation steps to measure the logistic performance of the considered system. The first step evaluates the possible decision alternatives, the second step the logistic performance of individual logistic objects and the third step the total system. Further research is directed towards the enhancement of the evaluation system to confirm the coherence between achievement of logistic objectives and level of autonomous control in job-shop production shown in Fig. 4.

A low level of autonomous control in conventional controlled logistics systems leads to a suboptimal achievement of logistic objectives. An increase of the level of autonomous control, e.g. by decentralisation of decision-making functions to the logistic objects causes a rise of the achievement of logistic objectives. However, at a certain level of autonomous control, a decrease of the achievement of logistic objectives caused by chaotic system behavior can probably be noticed. By dint of simulation studies the borders of autonomous control shall be detected to specify in which cases an increase of autonomous control does lead to higher performance of the system any more.

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