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Evaluation of Autonomously Controlled Logistic Processes

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Abstract
The implementation of autonomously controlled processes is a new approach to cope with nowadays demands on competitive companies due to increasing complexity. In order to proof whether autonomous logistic processes enable a better logistic performance compared to conventionally managed processes an appropriate evaluation system is necessary. Within this evaluation system the logistic objective achievement in relation to the level of autonomous control is determined. For this purpose a feedback loop in combination with a vectorial approach to measure the logistic performance and a catalogue of criteria to identify the level of autonomous control is developed.

Keywords:
Autonomous control, Production logistics, Evaluation

1 INTRODUCTION

Numerous change drivers of logistic processes, such as the development in the information and communication technology, enable a paradigm shift from central conventional planning and control to decentralized control by intelligent logistic objects. 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 characterized 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, and 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 ICT (information and communication technologies), for example RFID technology (Radio Frequency Identification) for identifying, GPS (Global Positioning System) for locating or UMTS (Universal Mobile Telecommunications System) for communicating of logistic objects [3]. The implementation of such autonomous controlled processes in production systems represents an approach coping with the requirements of increasing complexity.

These new approaches are currently investigated within the Collaborative Research Centre "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 explain the meaning of autonomous control and to show its potentials in logistic systems, particularly in production systems.

Therefore, it is essential to develop an adequate evaluation system in order to prove that the implementation of autonomous control in production systems is of advantage in relation to conventionally managed systems. At first 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 emphasize how conventionally managed and autonomous logistics processes differ. By dint of this catalogue it is possible to characterize a production system regarding its level of autonomy. Furthermore, it is necessary to determine the achievement of logistic objectives in production systems, especially in autonomously controlled systems. For this purpose a vectorial approach is developed, that allows to measure the logistic performance of individual logistic objects as well as the performance of the total system.

2 AUTONOMY IN PRODUCTION LOGISTICS

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 CRC 637, 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."[6]

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."

Based on this comprehension of autonomous control in the context of engineering science in the following chapter an evaluation system is presented that allows to prove the ability of autonomously controlled systems to cope with increasing complexity through a better accomplishment of logistic objectives.

3 ARCHITECTURE OF THE EVALUATION SYSTEM

The evaluation system represents the degree of logistic objective achievement related to the level of autonomous control. Therefore both the degree of the logistic objective achievement and the level of autonomous control must be measurable. Based on a catalogue of criteria the level of autonomous control of logistics systems can be determined with an adequate operationalisation. Furthermore, the logistic objective achievement can be ascertained through comparison of target and actual logistic performance figures related to the objectives low work in process, high utilization, low throughput time and high due date punctuality. The evaluation system consists of three evaluation steps to measure the logistic performance. The first step evaluates possible decision alternatives, the second step the logistic performance of individual logistic objects (e.g. orders or resources) and the third step the total system.

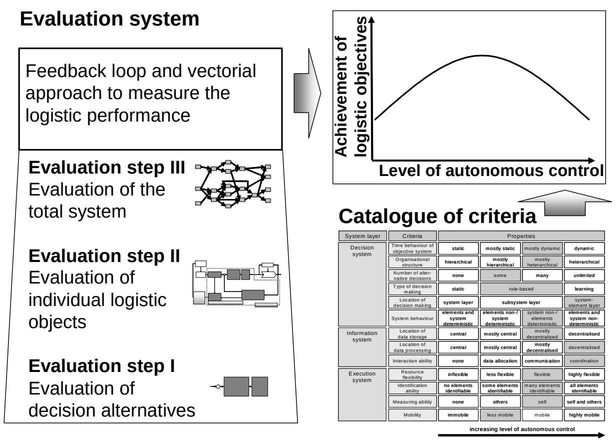

Figure 1: Logistic objective achievement vs. level of autonomous control

Further research is directed towards the enhancement of the evaluation system to confirm the coherence between logistic objective achievement and level of autonomous control on a job shop production floor as shown in figure 1. 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 decentralization of decision-making functions to the logistic objects causes a rise of the achievement of logistic objectives (comp. upper curve (right) in figure 1). However at a certain level of autonomous control a decrease of the achievement of logistic objectives can probably be noticed caused by chaotic system behaviour. By dint of simulation studies the borders of autonomous control shall be detected in order to specify in which cases an increase of autonomous control does lead to higher performance of the system. The level of autonomous control may be detected by the developed catalogue of criteria which will be presented in the following chapter.

4 CATALOGUE OF CRITERIA

The identification of autonomous cooperating logistic objects requires a dissociation from conventionally managed logistic objects. The definition of autonomous control explained before, 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, decentralized target system in combination with suited evaluation methods. In general, logistics systems probably 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 [7], 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.

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 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 figure 2.

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 →

Figure 2. Extract of catalogue of criteria for autonomously controlled systems [6]

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 visualized 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 production logistics scenario with the individual criteria and their marked properties are described in the following. Figure 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 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). One of the next steps within the development of the catalogue of criteria is the measurement of a concrete degree of autonomous control.

5 MEASUREMENT AND EVALUATION OF LOGISTIC OBJECTIVES

This chapter will focus on the measurement of the logistic performance of autonomous production logistic systems. Together with the measurement of the level of autonomous control explained in the previous chapter it allows an investigation of the coherence between the level of autonomous control and the performance of production systems.

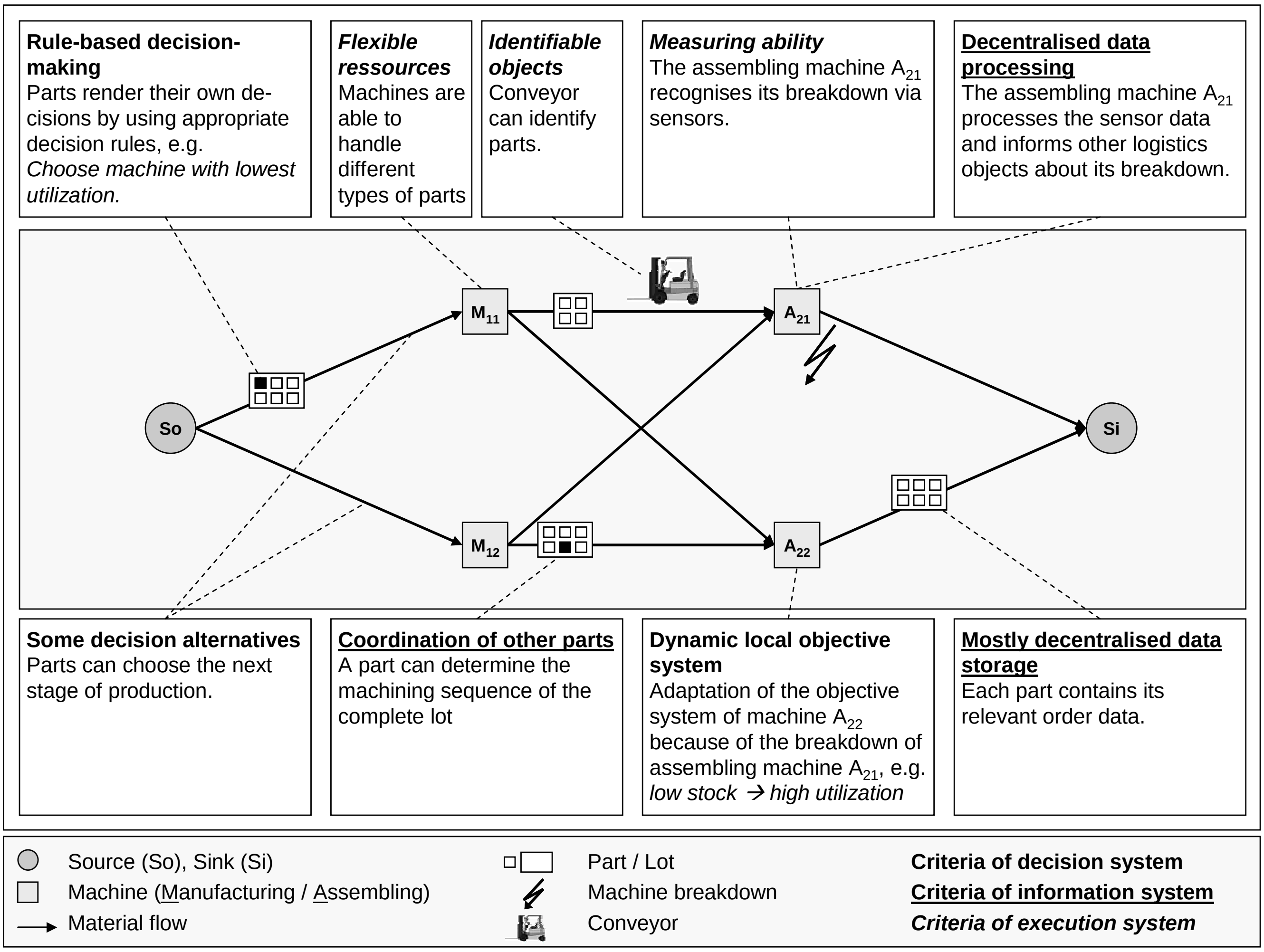

Figure 3: Autonomously controlled production logistic scenario [6]

5.1 Feedback loop of autonomous control

The basis for the measurement and evaluation of autonomously controlled logistic processes is a feedback control approach for individual logistic objects as shown in figure 4.

In this case the controlled process is a production process. Two logistic objects (an order object as well as a resource object) are involved in this process. Starting from a global system of objectives, target values for varying object classes are deduced. This enables for example from an order's point of view a differentiation between customer order and storage order with different target weights for delivery reliability and throughput time of an individual order. Local objectives for individual logistic objects arise based on the object classes objectives. These local objectives act as reference value for the feedback control approach for autonomously controlled processes. Eventual changes during the production process can immediately be realized through a feedback loop by measuring simultaneously the relevant logistic performance figures. Based on this feedback loop suitable solutions to react on process changes can be found by the evaluation of possible alternatives.

Within the controller (fig. 4) the deviations of the production process from the local desired values are analysed. All possible alternatives to react on the process deviation will be taken into consideration and are evaluated regarding its forecasted logistic performance. This first evaluation step (fig. 1) provides the basis for the following operation procedures of a logistic object through the production floor.

The evaluation-based decision will subsequently be executed by the actuator. For example this might be the transport to a different machine if the object decides to change the manufacturing system because of a higher potential of the degree of logistic objective achievement. At the completion of a production order the actual logistic performance figures are compared with the target performance figures (normative-actual value comparison). On this basis the degree of logistic objective achievement of an individual object is calculated. This determination represents the second step of the evaluation system. By taking all objects within the entire system into account and in combination with weights of different objects it is possible to determine the degree of logistic objective achievement for the overall system. The weighting of individual objects or object classes allows to emphasize the importance e.g. of bottleneck machines or specific customer orders. This consideration of the overall system represents the third step of the evaluation system. Through the decentralized feedback control of individual objects an opportunity is given to react on eventual changes or disturbances near real time and thus to increase the logistic performance of the overall system while measuring the individual degree of logistic objective achievement.

5.2 Vectorial approach to measure the achievement of logistic objectives

The concrete measuring of the degree of logistic objective achievement and the evaluation of alternatives will be done by means of a vectorial approach. Basis for this approach is a logistic objective vector z as shown in the following form:

$$z = \begin{bmatrix} \text{Due date reliability} \\ \text{Throughput time} \\ \text{Utilization} \\ \text{Work in process} \end{bmatrix} \quad (1)$$

This format of the vector applies for target vectors as well as for vectors with the actual values, which are used to determine the logistic performance figures to evaluate logistic objects and to evaluate decision alternatives. In order to consider different weights of the logistic objectives a weighting vector γ is introduced.

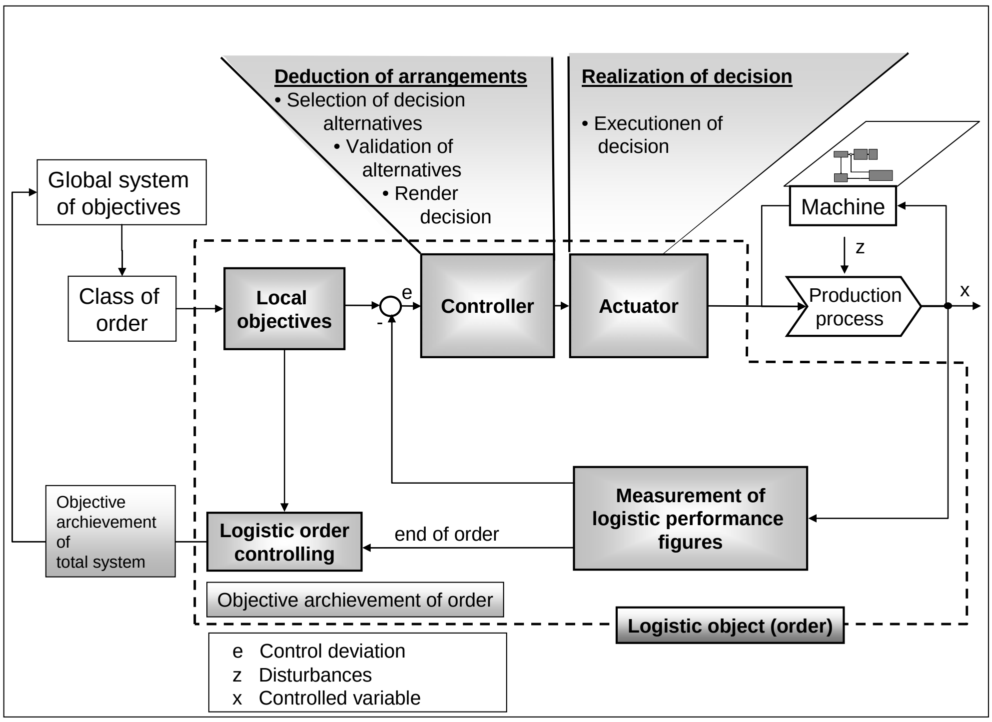

Figure 4: Feedback loop of autonomous control

The target value vectors of logistic objects contain of the desired values for the individual logistic objectives. By comparison of the target value vector z_{target} with the actual value vector z_{actual} it is possible to convert the thereby originated vector $\Delta z_{\text{target-actual}}$ in a vector $\boldsymbol{e}$ with the degrees of individual logistic achievement objective:

$$\Delta z_{\text{target}-\text{actual}} \Rightarrow \boldsymbol{e} = \begin{bmatrix} e_{\text{Due date reliability}} [\%] \\ e_{\text{Throughput time}} [\%] \\ e_{\text{Utilization}} [\%] \\ e_{\text{Work in process}} [\%] \end{bmatrix}, \quad (2)$$

with $e_{\text{Due date reliability}}$, $e_{\text{Throughput time}}$, $e_{\text{Utilization}}$ and $e_{\text{Work in process}}$ as degree of logistic objective achievement for each individual objective in [%].

The determination of the degree of logistic objective achievement takes place by normative-actual value comparison of the respective objective considering a given distribution, as shown in figure 5 using the example of due date variation.

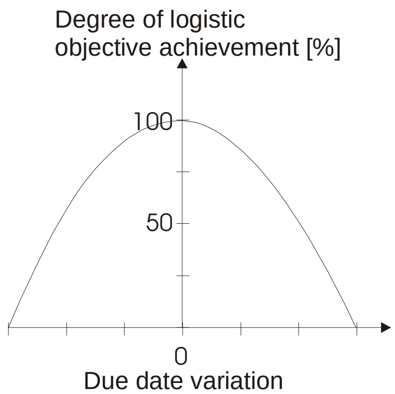

Figure 5: Determination of degree of objective achievement

By means of distributions of this type it is possible to determine the logistic objective achievement through reading the difference of target value vector and actual value vector in this diagram. In a next step the achievements of objectives are aggregated in one degree of logistic objective achievement for the individual object. This is done by introduction of the upper mentioned weighting vector for an individual object. Thus a possibility is given to determine the degree of logistic objective achievement e_{obj} in [%] for an object by calculating the scalar product of weighting vector γ and the vector $\boldsymbol{e}$ with the individual degrees of objective achievement:

$$\boldsymbol{e} \cdot \boldsymbol{\gamma} = \begin{bmatrix} e_{\text{Due date reliability}} [\%] \\ e_{\text{Throughput time}} [\%] \\ e_{\text{Utilization}} [\%] \\ e_{\text{Work in process}} [\%] \end{bmatrix} \cdot \begin{bmatrix} \gamma_{\text{Due date reliability}} \\ \gamma_{\text{Throughput time}} \\ \gamma_{\text{Utilization}} \\ \gamma_{\text{Work in process}} \end{bmatrix} = e_{\text{obj}} [\%] . \quad (3)$$

In this case it is very important that the sum of all γ_i within the weighting vector is exactly one to get a proper result in a percentage rate. Consequently, this equation describes the second step of the evaluation system. For the third step of the evaluation system it is essential to aggregate the objects achievement of objectives in one degree of logistic objective achievement for the total system. For this reason it is necessary to implement weights for individual objects, which describe the effects of single objects on the total system. In this manner it is furthermore possible to consider separately resource classes or order classes. The degree of logistic objective achievement for the total system e_{total} is accordingly determined by:

$$e_{\text{total}} = \frac{\sum_{i=1}^{n} \chi_i \cdot e_{\text{obj}}}{\sum_{i=1}^{n} \chi_i}, \quad (4)$$

with n as the number of all logistic objects within the system and χ as weighting factor of the logistic object. Through this calculation the degree of logistic objective achievement for production system is ascertainable. Together with the catalogue of criteria it is possible to determine the logistic performance in relation to the level of autonomy and thus to specify whether it is useful to increase or decrease the level of autonomy.

Figure 6 shows the application of the vectorial approach to measure the degree of logistic objective achievement by using the equations 1-3. Four logistic objectives are exemplarily demonstrated. In this case two orders and two machines are considered to ascertain the degree of logistic objective achievement.

It shows that the vectorial approach is an appropriate way to measure the logistic performance of individual logistic objects. By a consideration of all involved logistic objects and the usage of equation 4 the degree of logistic objective achievement for the entire system can be determined.

The three evaluation steps (comp. figure 1) can be represented through this vectorial approach. Furthermore this approach can be implemented in the feedback loop of autonomous control (comp. figure 4)

	Target value vector z_{target}	Actual value vector z_{actual}	Vector with degrees of logistic objective achievement e	Weighting vector γ	degree of objecitve achievement for each object e_{obj}
Order1	+/- 1 d <10 d - -	+ 1 d 11 d - -	100 % 90 % 100 % 100 %	0,8 0,2 0 0	$e_{obj} = 100 \cdot 0,8 + 90 \cdot 0,2 = 98\%$
Order2	+/- 1 d <20 d - -	2 d 21 d - -	90 % 95 % 100 % 100 %	0,2 0,8 0 0	$e_{obj} = 90 \cdot 0,2 + 95 \cdot 0,8 = 94\%$
Machine1	- - >80 % 50 h	- - 85 % 65 h	100 % 100 % 100 % 70 %	0 0 0,8 0,2	$e_{obj} = 100 \cdot 0,8 + 70 \cdot 0,2 = 94\%$
Machine2	- - >70 % 20 h	- - 60 % 18 h	100 % 100 % 85 % 90 %	0 0 0,2 0,8	$e_{obj} = 85 \cdot 0,2 + 90 \cdot 0,8 = 89\%$

d – Days
h – Hours

Figure 6: Application of the vectorial approach to determine the degree of logistic objective achievement

6 CONCLUSION

The new demands placed on competitive companies caused by increasing complexity like short product life cycles, decreasing number of lots with simultaneously rising number of product variants can not be fulfilled by todays planning and control methods. The actual research aims to show that the implementation of autonomously controlled processes will be an appropriate method to cope with these new requirements. While conventional production systems are characterized by central planning and controlling processes the idea of autonomously cooperating logistic processes is to develop decentralised and heterarchical planning and controlling methods. This paradigm shift requires a new evaluation system to measure the performance of autonomous production systems. For this purpose the logistic performance as well as the level of autonomy of production systems must be measurable. To determine the level of autonomous control a catalogue of criteria was developed which allows to characterise production systems regarding to its level of autonomous control. Furthermore, a feedback loop for autonomously cooperating logistic processes was introduced as well as a vectorial approach to determine the degree of logistic objective achievement. The three steps of the evaluation system enable an appraisal of decision alternatives, an evaluation of individual logistic objects and an evaluation of the total system itself. By usage of this evaluation system in simulation studies it is possible to determine the optimal level of autonomous control in a specific production system. The coherence between the level of autonomous control and the logistic performance is dependent on the systems complexity. For this reason it is necessary to do further research on the characterisation of complexity in production system as one component of the evaluation system.

7 ACKNOWLEDGMENTS

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