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2.4 Catalogue of Criteria for Autonomous Control in Logistics

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2.4.1 Introduction

Over the past years an increase in complexity of production and logistics systems regarding organisational, time-related and systemic aspects could be observed (Philipp et al. 2006). As a result, it is often impossible to make all necessary information available to a central entity in real time and to perform appropriate measures of control in terms of a defined target system. 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 (Scherer 1998). Hence, new demands were placed on competitive companies, which cannot be fulfilled with conventional control methods. Conventional production systems are characterized by central planning and control processes, which do not allow fast and flexible adaptation to changing environmental influences. Establishing autonomous control seems to be an appropriate method to meet these requirements. The major aim of establishing autonomous logistics processes is to improve the logistics system's performance. The basis for achievement of this objective is a comprehensive understanding of the term autonomy in the context of logistics processes. The idea of autonomous control is to develop decentralised and heterarchical planning and controlling methods in contrast to existing central and hierarchical planning and controlling approaches (Scholz-Reiter et al. 2006). 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 navigate through the production network themselves. The autonomy of logistic objects is possible due to recent developments by ICT (information and communication technologies), for example RFID technology (Radio Frequency Identification) for identification, GPS (Global Positioning System) for positioning or UMTS (Universal Mobile Telecommunications System) and WLAN (Wireless Local Area Network) for communication tasks (Böse and Lampe 2005). Furthermore comprehensive research in the field of agent-based computation in manufacturing (Monostori et al. 2006) is of particular importance for the implementation of autonomously controlled logistics systems.

These new approaches of autonomously controlled logistics systems are currently being investigated within the Collaborative Research Center 637 "Autonomous Cooperating 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 (Scholz-Reiter et al. 2004).

The intention of this article is to explain what is meant by autonomous control and describe its main criteria in contrast to conventional controlling methods in logistic systems. Therefore, a definition of autonomous control is introduced. The constituent characteristics of this definition are considered in a developed catalogue of criteria in the form of an operationalised morphological characteristic schema in order to describe autonomous logistic processes and emphasize how conventionally managed and autonomous logistic processes differ. The catalogue of criteria represents an instrument that allows characterising a considered logistic system concerning its level of autonomous control. The criteria and their properties are explained in a concrete way by investigating a production logistics scenario of a job shop manufacturing system. In conclusion, further research activities concerning evaluation of autonomous control are presented.

2.4.2 Definition of autonomous control

The vision of autonomous control emphasizes the transfer of qualified capabilities to logistic objects as explained above. According to the system theory, there is a shift of capabilities from the total system to its system elements (Krallmann 2004). 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 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." (Chapter 1 in this edited volume)

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 logistic systems is characterised by the ability of logistic objects to process information, to render and toexecute decisions on their own."

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

Decentralised decision-making in heterarchical systems

One feature of autonomous control is the capability of system elements to render decisions independently. Autonomy in decision-making is enabled by the alignment of the system elements in the form of a heterarchical organisational structure (Goldammer 2006). Therefore, decentralisation of the decision-making process from the total system to the individual system elements is a specific criterion of autonomous control. Each system element represents a decision unit which is equipped with decision-making competence according to the current task (Frese et al. 1996). 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 their own prioritisation. For example, the objective low work in process can be replaced in favour of high machine utilization by the machine itself. Thus the objective system of single elements is dynamic because of ability to modify prioritisation of the objectives over time, i.e. during the production process.

System element's ability of interaction

Decentralized decision-making processes require the availability of relevant information for the system elements. Consequently, the capability of system elements to interact with other 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, which 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, i.e. the ability of autonomous logistic objects to cooperate and coordinate activities of other objects, represents higher level of autonomous control.

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 on 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 sufficient to describe the transformation completely (Flämig 1998). Thus a fundamental criterion of autonomous control is that for the same input and values, there are different possibilities for transition to 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 a 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 autonomously controlled 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 individual consideration of the decentralised achievement of objectives (e.g. higher rate of on-time delivery, lower delivery times) of each single logistic object.

2.4.3 System layers of autonomous control

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 render and execute decisions. Each characteristic can be assigned to different layers of work in an enterprise. In accordance with Ropohl (Ropohl 1979), different layers of work can be classified in organisation and management, informatics methods and information and communication technologies as well as in flow of material and logistics. These layers relate to decision, information and execution systems. Figure 2.2 presents the assignment of the characteristics to the system layers, illustrates their correlations and introduces the main criteria of autonomous control.

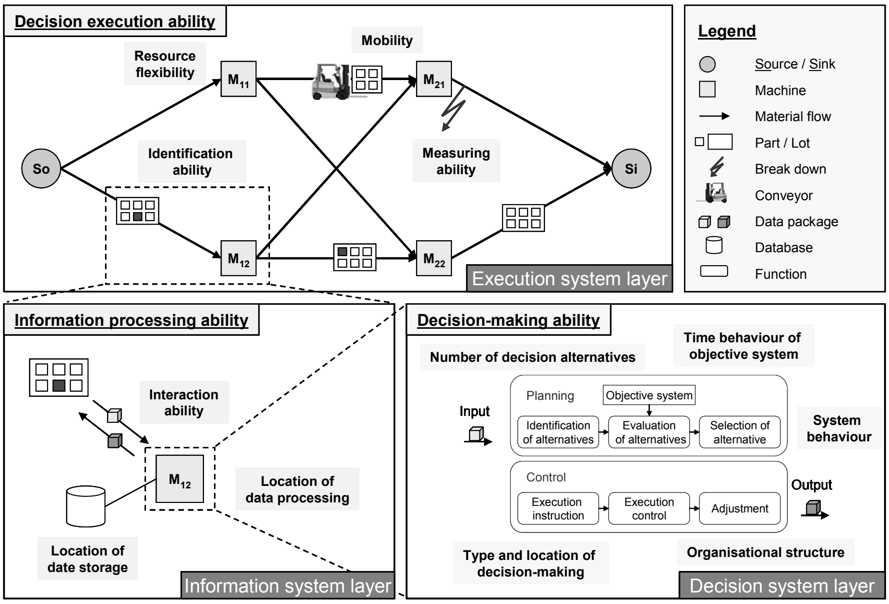

Fig. 2.2 System layers and criteria of autonomous control

The decision system is characterised by the decision-making ability. As mentioned before, in autonomously 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 a decentralised objective system, the selection, instruction and execution of the best rated alternative, as well as possible adjustments.

The basis for decision-making is the information processing ability on the information system layer. In autonomously 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 flexibly to unforeseeable, dynamic influencing variables. Mobility and high flexibility of the resources are other main criteria of autonomous control in production systems.

2.4.4 Derivation of a catalogue of criteria

The definition of autonomous control explained in a preceding chapter describes the maximum level of autonomous control. Thus, all system-elements in an absolutely autonomously controlled system are able to interact with other system elements and render decisions on the basis of an own, decentralized target system. In general, logistics systems probably contain both conventionally managed and autonomously controlled elements and sub-systems. Furthermore, it is assumed that there are different degrees or levels of autonomous control. For example, an individual part in a production lot can coordinate each production step of the lot which represents a high level of autonomous control; meanwhile, other parts only allocate data regarding their processing states. Consequently, the latter mentioned case shows a lower level of autonomous control.

In the following, a catalogue of criteria is derived in the form of a morphological scheme for characterising logistic systems based on their level of autonomous control. This catalogue of criteria consists of thirteen criteria as well as corresponding properties, which allow a first approximate analysis of autonomously controlled logistic order processing. With respect to the derivation and definition of the constituent criteria, there was no predetermination concerning dedicated domains of corporate logistics (Wiendahl 2005). On the contrary, each criterion was defined with a very high degree of abstraction to enable a universal application in different fields of logistics, for example in production logistics as well as transportation logistics.

According to the morphological scheme for characterising structures of order processing (Luczak et al. 1998) several demands regarding selection and description of criteria are defined as follows:

- Each criterion must concern the organisation as well as the planning and control functions of a logistic system;
- Each criterion must sufficiently describe the field from conventional control to autonomous control in logistic systems in the form of its properties;
- Each criterion must allow measuring and evaluating of its properties with adequate accuracy;
- The application of each criterion must be possible with an appropriate effort.

Criteria category	Criteria	Properties			
Decision-making criteria	Time behaviour of objective system	static	mostly static	mostly dynamic	dynamic
	Organisational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical
	Number of decision alternatives	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 processing criteria	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
Decision execution criteria	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. 2.3 Criteria and properties

For the purpose of structuring of the catalogue of criteria, three categories are introduced based on the system layer of autonomously controlled logistics systems described in the preceding chapter. These categories are decision-making criteria, information processing criteria and decision execution criteria. In figure 2.3 the criteria and their properties for autonomously controlled systems are illustrated in the form of a morphological scheme that contains the main criteria of autonomous control and its properties, which represent the different levels of autonomous control.

The vision of autonomous control encompasses transferring qualified capabilities (e.g. decision-making, data processing, measuring) from the total system to the system elements. So the visualized criteria 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 central decisions.

2.4.5 Operationalisation of the catalogue of criteria

The catalogue of criteria as described above allows a qualitative determination of the level of autonomous control of a considered logistic system. So it is possible to describe a logistic system as mainly autonomously controlled or rather conventionally controlled by means of the property allocation with an increasing level of autonomous control in their order from left to right in figure 2.3 The catalogue of criteria allows basically a comparison of different logistics systems regarding their level of autonomous control. The remarks concerning the definition and description of the term autonomous control in the context of logistics explained in the chapters before suggest that the criteria do not all have the same influence on the determination of the level of autonomous control. For example the criterion location of decision-making seems to be a more important characteristic for autonomously controlled logistic systems than the criterion resource flexibility. For this reason an operationalisation of the catalogue of criteria seems necessary to ensure a precise determination of the level of autonomous control and allow an accurate comparison of logistic systems regarding their level of autonomous control.

For the purpose of evaluating the level of autonomous control of a considered logistics system the method of the value-benefit analysis, a frequently used evaluation method in practise, seems to be suited. Subject matter of the value-benefit analysis is the investigation of a number of complex alternatives in order to arrange these options according to the preferences of the decision maker by a multidimensional system of objectives in terms of values of benefit (Zangemeister 1976). In the present investigation the aim of the application of this method is not the determination of the top-rated alternative by means of a multidimensional system of objectives, but rather the evaluation of the level of autonomous control of a considered logistics system on the basis of constitutive criteria of autonomous control. However, the methodological procedure is the same except for the comparison of the total evaluation values of different alternatives which is not done in the case of the catalogue of criteria.

As a first step, each criterion of autonomous control is defined and assigned to the criteria categories: decision-making criteria, information processing criteria and decision execution criteria. After that, the weight of each criterion is ascertained. These weightings assign the importance of each criterion in the evaluation of the level of autonomous control. For the determination of the criteria weights, a systematic method in form of a pairwise comparison is made (Eversheim and Schuh 1996) as illustrated in figure 2.4.

Pairwise Comparison

Legend

2 = A is more important than B

1 = A is equal to B

0 = A is less important than B

		A												
		Time behaviour of objective system	Organisational structure	Number of decision alternatives	Type of decision-making	Location of decision-making	System behaviour	Location of data storage	Location of data processing	Interaction ability	Resource flexibility	Identification ability	Measuring ability	Mobility
B	Time behaviour of objective system		2	2	0	2	2	0	0	2	0	0	0	0
	Organisational structure	0		1	0	2	1	0	0	2	0	0	0	0
	Number of decision alternatives	0	1		0	2	1	0	0	2	0	0	0	0
	Type of decision-making	2	2	2		2	1	0	1	2	0	0	0	0
	Location of decision-making	0	0	0	0		0	0	0	1	0	0	0	0
	System behaviour	0	1	1	1	2		0	0	2	0	0	0	0
	Location of data storage	2	2	2	2	2	2		2	2	1	2	2	1
	Location of data processing	2	2	2	1	2	2	0		1	0	1	1	0
	Interaction ability	0	0	0	0	1	0	0	1		0	0	0	0
	Resource flexibility	2	2	2	2	2	2	1	2	2		2	2	0
	Identification ability	2	2	2	2	2	2	0	1	2	0		2	0
	Measuring ability	2	2	2	2	2	2	0	1	2	0	0		0
	Mobility	2	2	2	2	2	2	1	2	2	2	2	2	
Total		14	18	18	12	23	17	2	10	22	3	7	9	1
Priority		6	3	3	7	1	5	12	8	2	11	10	9	13
Weighting		9	12	12	8	15	11	1	6	14	2	4	6	1

Fig. 2.4 Pairwise comparison

Using this evaluation method, every criterion is compared with each other regarding its importance to determine the level of autonomous control. Accordingly it is investigated if criterion K_n is more important, is equal or is less important than criterion K_{n+1}. The results of the pairwise comparison are compiled in a two-dimensional matrix. By computing the total values for each criterion, the priority and consequently the weighting of each criterion can be determined, which describes the importance of each criterion concerning the evaluation of the level of autonomous control. The weightings of this pairwise comparison are a first possible result, which allows an approximate rating of the importance of each criterion to describe autonomous control in logistics.

As a second step, the considered logistics system is evaluated concerning the fulfilment of each criterion by selecting the corresponding property (compare following chapter). Each property of a criterion contains a fulfilment value which is uniformly distributed in the range of 0 (absolutely conventionally controlled) and 3 (absolutely autonomously controlled) with an increasing level of autonomous control in their order from left to right in figure 2.3. After that, weighted evaluation values are calculated by multiplication of weight and fulfilment of respective criteria. Finally, the total evaluation, i.e. the level of autonomous control, can be calculated by summarizing the weighted evaluation values. As a consequence the level of autonomous control in an absolutely conventionally controlled logistics system is 0 because all fulfilment values are 0, whereas the level of autonomous control in an absolutely autonomously controlled logistics system comes to a total evaluation value of 468. In general, the level of autonomous control probably lies in between these extreme total evaluation values.

2.4.6 Application of the catalogue of criteria

In this chapter, criteria and properties as well as the methodical approach to determine the level of autonomous control of a considered logistics system are illustrated using a production logistics scenario. Figure 2.5 gives an overview of a scenario of two-stage job shop production. Each criterion characterises the behaviour of logistic objects and is assigned to the decision-making system layer, information system layer or execution system layer.

The first production stage entails 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). At a pre-determined 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 the disturbance is recognised and the production plan is adjusted in the traditional way.

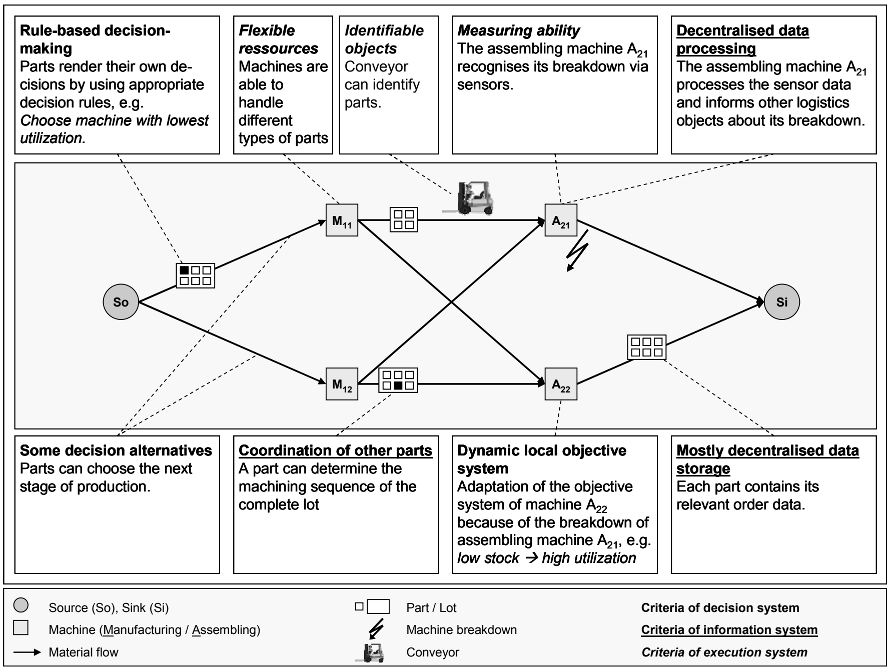

Fig. 2.5 Autonomously controlled production logistics scenario

The autonomous control of the machines provides the opportunity to react fast and flexibly to disturbances. Machine A_{21} autonomously recognises its breakdown by constant measuring and processing of the sensors data. Deviations of the sensors data are identified, analyzed 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 prioritizing the objective of 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 allow 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.

The level of autonomous control of the production logistics scenario introduced above can be determined using the catalogue of criteria as illustrated in figure 2.6.

Criteria category C_i	Criteria C_{ij}	Weighting G_{ij}	Properties P_{ij}			
Decision-making criteria	Time behaviour of objective system	9	static 0	mostly static 1	mostly dynamic 2	dynamic 3
	Organisational structure	12	hierarchical 0	mostly hierarchical 1	mostly heterarchical 2	heterarchical 3
	Number of decision alternatives	12	none 0	some 1	many 2	unlimited 3
	Type of decision making	8	static 0	rule-based 1,5		learning 3
	Location of decision making	15	system layer 0	subsystem layer 1,5		system-element layer 3
	System behaviour	11	elements and system deterministic 0	elements non-/ system deterministic 1	system non-/ elements deterministic 2	elements and system non-deterministic 3
Information processing criteria	Location of data storage	1	central 0	mostly central 1	mostly decentralised 2	decentralised 3
	Location of data processing	6	central 0	mostly central 1	mostly decentralised 2	decentralised 3
	Interaction ability	14	none 0	data allocation 1	communi-cation 2	coordination 3
Decision execution criteria	Resource flexibility	2	inflexible 0	less flexible 1	flexible 2	highly flexible 3
	Identification ability	4	no elements identifiable 0	some elem. identifiable 1	many elem. identifiable 2	all elements identifiable 3
	Measuring ability	6	none 0	others 1	self 2	self and others 3
	Mobility	1	immobile 0	less mobile 1	mobile 2	highly mobile 3

Level of autonomous control

$$\sum_{i=0}^{n} \sum_{j=0}^{n} G_{ij} * p_{ij} = 220$$

C_i = Criteria category
C_{ij} = Criterion
G_{ij} = Weighting of criterion
P_{ij} = Property of criterion
p_{ij} = Fulfilment of criterion

Fig. 2.6 Application of catalogue of criteria

The properties of each criterion are ascertained on the basis of the description of the production logistics scenario. After that, weighted evaluation values are calculated by multiplication of criteria weighting as described in the preceding chapter and fulfilment of respective criterion. The total evaluation, which aggregates to 220, represents the total of all weighted evaluation values and is defined as level of autonomous control of the considered production system.

On the basis of this production logistics scenario it has been shown that each logistic system can be classified according to the level of autonomous control by means of the introduced catalogue of criteria. As a result the catalogue of criteria is an appropriate tool for comparing logistics systems regarding their level of autonomous control and therefore for evaluating fields of application of autonomous control, for example, by using simulation studies.

2.4.7 Conclusions and outlook

In this paper a catalogue of criteria was introduced to describe autonomous control in logistics systems. Based on the definition of autonomous control and its main characteristics in the context of logistics, the catalogue of criteria was developed. The catalogue of criteria represents an easy to use tool that affords an approximate analysis of a logistics system concerning its level of autonomous control. The catalogue of criteria allows both the characterisation of an existing as well as a future logistics system concerning its level of autonomous control by determination of the properties of each criterion. Furthermore, two different logistic systems can be compared regarding their level of autonomous control. The last mentioned point is of particular importance due to the fact that this comparison allows an evaluation of the fields of application of autonomy in logistics.

The application of autonomous control in logistics is based on the supposition that the allocation of planning and control tasks to autonomously controlled logistics objects results in a higher achievement of logistic objectives because of a better coping with high complexity in today's logistics systems. However, at a certain level of autonomous control, a decrease of the achievement of logistic objectives seems probable as a result of chaotic behaviour.

To verify this thesis an evaluation system for autonomously controlled logistics systems is necessary that meets the following demands:

- Determination of the level of autonomous control of the considered logistics system;
- Ascertaining of the level of complexity of the considered logistics system;
- Measuring of the logistic objective achievement of the considered logistics system.

Only if an evaluation system meets these demands, it is possible to make a statement on which level of complexity an autonomously controlled logistics system leads to a better achievement of logistic objectives compared to conventional control. Based on these demands an evaluation system of autonomously controlled logistics systems was developed, which is illustrated in figure 2.7.

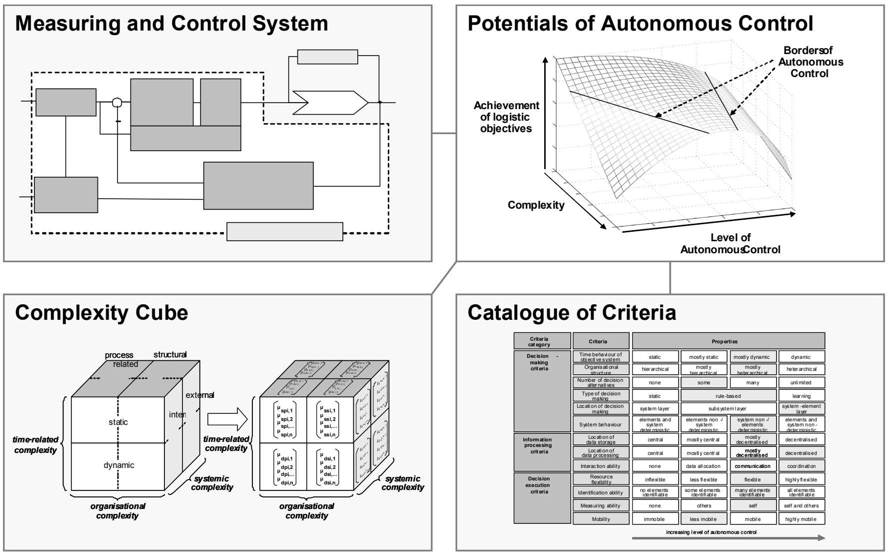

Fig. 2.7 Evaluation system of autonomously controlled logistics systems

Future research is directed to further development of the catalogue of criteria, especially detailing and completion of its criteria, as well as the advancement of the other components of the evaluation system pictured in figure 2.7. The complexity cube allows the description of the complexity of a considered logistics system regarding time-related, organisational and systemic aspects. By means of the measuring and control system, 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 utilization, low throughput time and high due date punctuality. Through simulation studies using the developed evaluation system, it is anticipated that the borders of autonomous control can be found, specifying in which cases an increase of autonomous control does not lead to correspondingly higher performance of the logistics system.

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