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Development of a catalogue of criteria for the evaluation of the self-organization of flexible intralogistics systems

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Abstract

The approach of self-organized and autonomous controlled systems offers great potential to meet new requirements for the economical production of customized products with small batch sizes based on a distributed, flexible management of dynamics and complexity within the production and intralogistics system. To support the practical application of self-organization for intralogistics systems, a catalogue of criteria for the evaluation of the self-organization of flexible logistics systems has been developed and validated, which enables the classification of logistics systems as well as the identification and evaluation of corresponding potentials that can be achieved by increasing the degree of self-organization.

Keywords: Intralogistics; Self-organization; Autonomous control; Flexible intralogistics systems; Catalogue of criteria;

1. Introduction

In order to compete, manufacturing companies have to be able to deliver on time at the lowest possible cost. However, the achievement of the companies' objectives is hampered by dynamic influences. Shorter product lifecycles, decreasing batch sizes and an increasing number of variants and complexity of products and processes are major challenges that have an ever greater impact on production and logistics [1, 2].

In individualized production, each product differs from the previous products in terms of the required manufacturing and assembly processes as well as the required components and their flow through the factory. Real-time configuration, control and decision making within these flexible factory environments are becoming the key challenges. New methods and systems based on self-organized or self-controlled systems and the theory of the Internet of Things offer promising solutions for the organization, planning and control of flexible material flow systems within networked production environments. In order to keep pace with the increased flexibility requirements of production, this shall enable the configuration and regulation of material flow at any point of the material flow system. For example, self-organized or self-controlled, decentralized material flow control systems will distribute the necessary decision and control processes to intelligent logistic units (such as transport units, conveyor modules and software services) [3]. In this way, humans, machines and objects in the production environment will jointly decide, which tools and machines are to be used and with which means of transport components and (semi-finished) products are to be transported to the next production step. In this self-organized scenario, humans get a real-time overview of production and can react quickly in case of complications [4]. This paradigm shift requires far-reaching organizational and management changes on the side of the companies interested in a future deployment, which may require investments in new or adapted hardware and software components as well as product adaptations and further qualification of employees, depending on the initial situation of the companies [5]. As in the past, this further development towards self-organized production systems will therefore have to be carried out in an evolutionary manner, as the investments in existing infrastructure must first be amortized from the

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companies' perspective and a company-specific roadmap must be developed [6]. Therefore, the identification of corresponding potentials within the companies' logistics processes is a decisive prerequisite. For this reason, a catalogue of criteria has been developed, which helps to determine the degree of self-organization of logistic systems and processes and to identify and evaluate potentials for increasing the degree of self-organization.

At the beginning of this research work, a characteristics-based differentiation of the terms of "self-organization" and "autonomous control", which are often used synonymously in literature, was undertaken based on a literature analysis.

For the modelling and structuring of flexible, self-organized logistics systems, the process chain model according to *Kuhn* [7], the fractal factory according to *Warnecke et. al.* [8] and the the viable system model (VSM) according to *Beer* [9] and *Redlich et al.* [10] were analyzed in detail. In addition, the state of the art and science with regard to approaches and methods for the assessment of autonomous control and self-organization of intralogistics systems has been investigated. Based on the investigated state of the art and science, a catalogue of criteria and a corresponding procedure have been developed to determine the degree of self-organization of existing logistic systems and to identify and evaluate potentials, which can be achieved by an increase of the degree of self-organization. The developed catalogue of criteria was validated qualitatively based on literature as well as quantitatively on the basis of a conventional centrally organized intralogistics scenario and a scenario with a higher degree of self-organization which have been set up at the factory environment "Werk150" at Reutlingen University.

2. Self-organization and autonomous control

In the context of the fourth industrial revolution, the topic of a flexible and distributed decision on the configuration of logistic systems in the sense of self-organization is becoming increasingly important, since the processes of logistic subsystems have to be coupled effectively and efficiently [11, 12]. The collective term "self-organization" has preoccupied almost all scientific disciplines since the early 1960s. The central object of investigation of this concept is the spontaneous formation of an order in dynamic systems, without the need for equilibrium [13]. Autonomous control is based on the foundations of the interdisciplinary idea of self-organization. Autonomous control in general describes the ability of a system to shape itself with its own means [14].

2.1. Major characteristics of self-organization and autonomous control

Even though the concept of self-organization is not a detailed and verified "theory of self-organization", there is an agreement in the literature about certain characteristics. Central characteristics, which are part of numerous self-organization approaches and definitions, are the characteristics of complexity, dynamics, non-determinism, autonomy, redundancy, interaction and emergence [15]. The systems considered in the context of self-organization are always dynamic, complex systems. They are all based on the existence of numerous interrelationships between the system elements themselves and between the system and its environment. These interrelationships mean complexity for the systems, which is to be solved by the use of self-organization [15, 16].

The potentials and the application of the concept of autonomous control in the field of logistics were widely investigated in the Collaborative Research Centre 637 "Autonomous Cooperating Logistic Processes – A Paradigm Shift and its Limitations" (SFB 637) (see amongst others [17, 18]). In line with the SFB 637, autonomous control is interdisciplinarily defined as processes of decentralized decision-making in non-hierarchical structures. It implies that interacting elements in non-deterministic systems have the ability and possibility to make decisions autonomously. The objective of the application of autonomous control is a higher robustness and positive emergence of the overall system by a distributed, flexible handling of dynamics and complexity [19]. According to *Wycisk* [20], autonomous controlled logistics systems require interacting heterogeneous logistics elements, which have the ability and possibility to make autonomous decisions in order to meet specific logistics objectives [20].

2.2. Differentiation of the terms »self-organization« and »autonomous control«

Comparing the terms of "self-organization" and "autonomous control", the concept of self-organization often serves in science as an anti-pole to central, hierarchical organization of systems, and describes the way, in which order is created from within the respective system itself. At the subsystem level, self-organization is reflected in the adaptability of a system to changing external conditions. In order to carry out these adaptations, autonomously acting elements in the subsystems are necessary, which can fulfil a targeted-oriented self-adjustment to enable an adaptation of the subsystem by means of their individual actions [11, 20, 21].

Autonomous control generally describes the ability of a system to give itself a shape with its own means [14]. Therefore, autonomous control pursues the goal of decentralized decision-making. At system level, this is enabled in particular by the possibility of partial self-regulation. This self-regulation has to be partial, because decisions can only be made within defined boundaries. This enables e.g. transport vehicles or individual employees to solve problems independently at element level [20].

For a more detailed characteristics-based differentiation of autonomous control and self-organization, please also see *Windt* [22] and *Schuhmacher* [23]. In general, it can be stated that the phenomenon of self-organization is more strongly observed at the global system level, while autonomous control is more predominant at the level of individual system elements [24]. In addition the approach of self-organization is stronger focused on human (corporate) organizations and the integration of humans, while the approach of autonomous control is more oriented on the processes of establishing order in technical systems at the execution or shop floor level.

3. Catalogue of criteria for the evaluation and potential identification of self-organized intralogistics systems

Numerous papers dealing with the analysis and evaluation of specific logistics systems, such as picking systems (e.g. *Galka et al.* [25], *Huber* [26]), storage and retrieval systems (e.g. *Epp* [27]) or tugger train systems (e.g. *Klenk et al.* [28], *Martini et al.* [29]), have been identified. Following the objective of this research, the focus had to be set on (preferably) holistic methods and models that allow a characteristics-based evaluation and analysis of self-organized or autonomous controlled logistics systems without being limited to specific logistics systems or logistics processes. In this respect, only the evaluation system for autonomous controlled logistics systems according to *Böse et al.* [30] has been identified as an existing, characteristics-based evaluation method. To enable the identification and evaluation of potentials for increasing the degree of self-organization of logistic processes and systems, a catalogue of criteria and procedure has been developed, which will be further described in the following.

3.1. Aims and assumptions

The aim in developing the catalogue of criteria for evaluating the self-organization of flexible logistics systems was that it should include characteristics and corresponding criteria at a high level of abstraction, similar to the approach of *Böse* [30, 31]. This enables the evaluation of different logistics systems (e.g. intralogistics systems or entire supply chains) with as few criteria as possible. Furthermore, the assumption is made that the limits of self-organization with regard to the achievement of logistic objectives as well as the complexity and degree of self-organization of the considered system are in line with those assumed by *Scholz-Reiter* [32]. For example, it is assumed that the optimal degree of self-organization in a complex logistical system with regard to the achievement of logistical objectives does not correspond to the maximum degree of self-organization of the investigated system (also see the graph in the center of Fig. 2). This assumption can be further supported by sources such as *Wehberg* [11], *Hülsmann et al.* [15] and *Wycisk* [20]. In order to fulfil specific (logistical) target variables, these sources consider an interplay of external (decentralized decision-making) and self-organization or the self-organization of selected functions or organizations within logistical systems to be beneficial. Following *Wiendahl* [1] the overall aim of production logistics is to enhance logistics performance and to reduce logistics costs to improve the economic efficiency.

3.2. Procedure for system classification and potential identification

The starting point for identifying the potential through the implementation of self-organization in logistic systems is the selection of the logistic system to be considered and the definition of the system boundaries. The next step is the determination and analysis of the logistical target achievement of the system under investigation in order to determine deviations from the logistical target values (see Fig. 1).

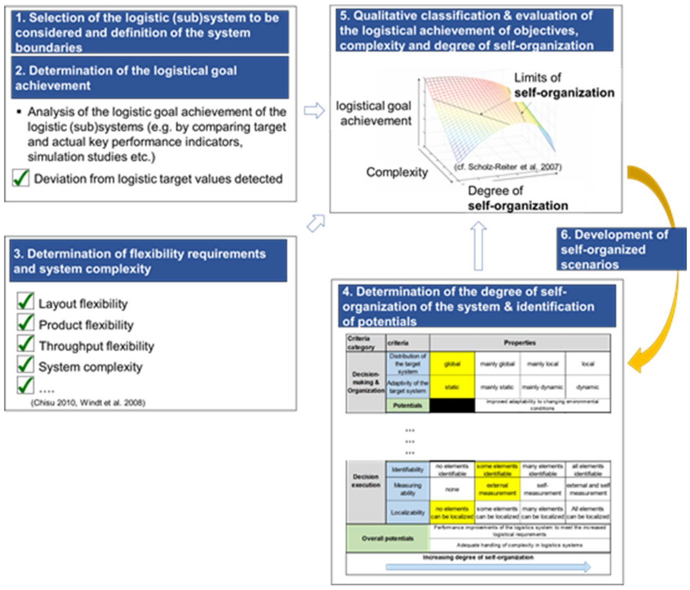

Fig. 1. Procedure for system classification and potential identification for self-organization

These deviations provide the starting point for the investigation of the potential for implementing self-organization. In case of very complex systems with numerous system elements, a further subdivision of the overall system into sub-systems can be considered in order to enable a more detailed investigation of the logistical goal achievement at system and system element levels. The third step is the determination of the flexibility requirements and complexity of the logistic system under consideration, e.g. by applying the "Complexity cube" of *Windt et al.* [33]. Afterwards, the logistic system is classified in the developed criteria catalogue in order to determine the degree of self-organization of the logistic system. Based on the determined degree of logistic goal achievement, complexity and self-organization, the classification of the logistic system is carried out to estimate the potential for an increase in the degree of self-organization. The catalogue of criteria with its potentials assigned to the criteria serves as a general framework for the development of system- or company-specific self-organization scenarios with the aim of improving the achievement of logistical objectives. For example, if the initial logistics system is classified in the criterion "Adaptability of the target system" in the lowest degree of "static", an increase of the degree of self-organization can be achieved by dynamic target systems within the logistics system. Following the catalogue of criteria, the potential for an improved adaptability to changing conditions can thus be achieved (also see Fig. 2). The scenarios generated in this way are then to be checked for feasibility, e.g. based on simulation studies or pilot tests. Due to the closed-loop character of this approach, the optimal degree of self-organization for the respective logistic system can be determined step-by-step and iteratively.

3.3. Catalogue of criteria

In order to determine the degree of fulfilment of logistic systems in relation to the criteria of the catalogue of criteria, the characteristics of each criterion were ranked in a morphological box with ascending fulfilment values from left (0: No self-organization) to right (3: Complete self-organization) in accordance with *Böse* [30, 31]. By adding up all fulfilment values, the degree of self-organization of a system can be quantified based on the total fulfilment value. In addition, corresponding potentials have been assigned to the criteria and their characteristics based on a literature study. This assignment of potentials to the respective criteria and characteristics enables the identification of corresponding potentials when the degree of self-organization of the system classified in the catalogue of criteria is increased. Nevertheless, it should be noted that some potentials cannot be achieved in strict isolation. The criteria categories have been selected to reflect the functional levels of organization and management ("Decision-making & organization"), information and communication technologies ("Information processing") and material flow and logistics ("Decision execution"), on which self-organization and autonomous control strategies are imposing changes in companies [31, 34].

4. Application and validation of the catalogue of criteria at Werk150

For a practice-oriented application and validation of the catalogue of criteria, an initial scenario with a low degree as well as a scenario with a higher degree of self-organization in the field of intralogistics transports have been developed and implemented at "Werk150". Werk150 is the research, education and training factory on the campus of Reutlingen University, accommodating various industrial logistics, assembly and manufacturing infrastructure to realize changeable production scenarios. The scenarios for the validation of the catalogue of criteria were focused on the intralogistics material supply processes from the material supermarket to predefined workstations with fixed source-sink relations. Following the procedure described in section 3.2, a deviation of the logistical goal achievement (logistics performance and costs) has been detected in the hierarchically organized initial scenario as the starting point for the investigation, and the flexibility requirements and system complexity have been determined. Afterwards, the initial scenario with a low degree of self-organization has been classified in the catalogue of criteria (marked blue) and a scenario with a higher degree of self-organization (marked green) was developed based on the criteria, properties and stated potentials for an increase of self-organization of the catalogue of criteria. The explanation of the scenarios as well as the major criteria and potentials stated in the catalogue of criteria will be done in the following based on the criteria categories of "Decision-making & organization", "Information processing" and "Decision execution" (also see Fig. 2).

4.1. Decision-making & organization

The criteria category of "Decision-making and organization" includes the initiation of the decision and structure formation process, the determination and evaluation of decision alternatives as well as the triggering of the implementation and review of the selected decision alternative.

Criteria category	Criteria	Properties			
Decision-making & Organization	Distribution of the target system	0 Global	1 Mainly global	2 Mainly local	3 Local
	Adaptivity of the target system	0 Static	1 Mainly static	2 Mainly dynamic	3 Dynamic
	Potentials		Improved adaptability to changing environmental conditions		
	Organizational structure	0 Hierarchical	1 Mainly hierarchical	2 Mainly heterarchical	3 Heterarchical
	Change capability of the organization	0 Low	1 Medium	2 High	3 Very high
	Potentials		A dynamically initiated structure formation process allows it to meet changing system and environmental requirements within the shortest possible time and thus secure the competitiveness of the company.		
	Number of decision alternatives	0 None	1 Some	2 Many	3 Unlimited
	Type of decision-making	0 Extrinsic (static)	1,5 Intrinsic (rule-based)		3 Intrinsic (learning)
	Place of decision-making	0 System level	1,5 Subsystem level		3 System element level
	Human role	0 Passive, executing	1 Mainly passive, executing	2 Mainly aktive, co-decisive	3 Actively decisive
	Potentials		Continuous system development and strategic goals of the company can be met and undesirable developments can be avoided.		
			Targeted use of the creative and creative abilities, professional competences and knowledge of the human being to improve the system performance and the achievement of goals.		
	Predictability of system/ element behavior	0 Elements and system deterministic	1 Elements non-/system deterministic	2 System non-/elements deterministic	3 Elements and system non-deterministic
Information processing	Location of data storage	0 Central	1 Mainly central	2 Mainly decentralized	3 Decentralized
	Location of data processing	0 Central	1 Mainly central	2 Mainly decentralized	3 Decentralized
	Potentials		Improvement of robustness and data availability in the overall system		
	Ability to interact	0 None	1 Data provision	2 Communication	3 Coordination
Decision execution	Flexibility	0 Inflexible	1 Little flexibility	2 Flexible	3 Very flexible
	Potentials		Enabling/improved management of complexity and dynamics in the system		
	Identifiability	0 No elements identifiable	1 Some elements identifiable	2 Many elements identifiable	3 All elements identifiable
	Measuring ability	0 None	1 External measurement	2 Self-measurement	3 External and self-measurement
	Localizability	0 No elements can be localized	1 Some elements can be localized	2 Many elements can be localized	3 All elements can be localized
Overall potentials		Performance improvements of the logistics system to meet the increased logistical requirements			
		Adequate handling of complexity in logistics systems			
Increasing degree of self-organization →					

Fig. 2. Extract of catalogue of criteria for self-organization (cf. [30, 31])

In the initial hierarchically organized scenario, the decision-making and organization is conventionally structured, based on a centralized pre-planning, decision-making and a hierarchical organizational structure. In the self-organized scenario, the decision-making capabilities regarding the intralogistics transport have been mainly transferred to the autonomous transport systems at Werk150. For example the transport systems are aiming on minimizing costs and maximizing their performance with a variable prioritization when they are bidding on the transport orders that have to be fulfilled. This opens up the potential for improved adaptability of logistic systems to changing conditions (like changing transport volumes) as stated in the catalogue of criteria [22, 35].

A specific feature of self-organization is its ability to create order dynamically to allow goal-oriented structural adjustments. The ability of dynamic, goal-oriented restructuring of self-organized systems through their system elements can also be found in the approach of the Fractal Factory [8] and the VSM [9]. Therefore, the criterion "Change capability of the organization" has been added to the catalogue of criteria. This dynamically initiated structure formation process, which has been partially realized within the implemented self-organized scenario for the autonomous structuring of the transport systems to fulfil the upcoming transport orders, opens up the potential to react proactively and in a goal-oriented manner to changing requirements in the logistics system [8].

In contrast to the more technically oriented approach of autonomous control, the role of the human worker as an actively decisive system element with defined decision-making and action competences must be considered as a further criterion for determining the degree of self-organization. In classical hierarchically organized systems, employees often have almost no room for manoeuvre, following the classical management and organizational view, in which the supervisor is regarded as the source of knowledge [36]. As the degree of self-organization increases, more and more competences and freedom of action and decision-making are transferred to the employee. The role of the employee thus changes from a passive to an actively shaping, independently acting and decisive role in the system. By granting a defined freedom of action and a targeted support of the employee by the supervisor, the potential for a continuous further development of the system can be achieved and at the same time the strategic goals of the company can be maintained [8]. The aspect of giving defined co-decisive competences to the human workers, have been realized in a first version within the self-organized scenario at Werk150 based on a so-called "Worker client"-app which enables the worker to interact with the autonomous controlled intralogistics system, e.g. to receive manual transport orders or to solve arising conflicts in the intralogistics system which cannot be solved by the autonomous systems.

4.2. Information processing

The criteria category of "Information processing" is dedicated to the criteria for determining the way in which information is collected, stored, transformed and transferred [22]. Decentralized data storage and data processing at the system element level is characteristic for the autonomous control and self-organization of logistics systems. This allows the autonomous transport system in the self-organized scenario to manage the planning, control and structure formation processes autonomously. Decentralized data storage and processing in material flow systems can lead to a higher data availability as well as to a higher robustness and flexibility of the system [37]. Thus, for example, the failure of a single autonomously controlled transport system in the self-organized scenario does not lead to a standstill of the overall logistics system, since the ability to store and process data is distributed redundantly in the system. The criterion of "Ability to interact" describes the ability of logistical objects to communicate with other logistical objects in the system and to exchange data in order to obtain and process information about the system environment. The availability and exchange of this information is a central prerequisite for the self-organization of logistical elements and systems. The characteristics of this criterion thus range from a lack of any ability to interact as in the initial scenario, the provision of certain information, the communication of objects (exchange of information) to "coordination" as for the autonomous transport systems in the implemented self-organized intralogistics scenario enabling a goal-oriented task execution and intralogistics system (re-)structuring [31].

4.3. Decision execution

The criteria category of "Decision execution" comprises the relevant criteria for implementing the decision taken at the material flow level [22]. On the execution level, the approach of self-organization requires a high degree of flexibility of resources as well as the possibility of identifying and localizing all system elements for the implementation of structural changes of the logistic system. For the self-organized intralogistics scenario at Werk150, amongst others, autonomous transport systems have been implemented that are capable to navigate freely thorough the factory (layout flexibility) and are capable to transport different types of products and bins (goods flexibility). Such a flexible intralogistics system offers the potential to be more adaptable to changing conditions and to be used in a more versatile way [38].

4.4. Quantitative analysis and validation

The quantitative analysis of the investigated scenarios with a low and medium degree of self-organization showed amongst others a lead time reduction of up to 30 % for the self-organized scenario and improved adherence to schedule (increased logistics performance) as well as significant improvements of the utilization of the transport systems (reduction of logistics cost) (also see *Grosse-Erdmann et al.* [39]-in publication). The potentials of the more self-organized scenario considering costs and performance goals have proved to be especially significant for intralogistics situations with dynamic turbulences (such as transport system breakdowns or rush orders). This generally supports the potential of an overall performance improvement of the logistics system by increasing the degree of self-organization as stated in the catalogue of criteria described above.

5. Conclusion and outlook

In conclusion, it can be stated, that various potentials to improve the logistic goals are arising in particular from the combination of the characteristics and abilities of autonomous control and self-organization that have been considered in the developed catalogue of criteria. For example, the concept of autonomous control can make a valuable contribution in the area of operative decentralized and target-oriented decision-making at the level of logistical objects in the material flow system. On the other hand, the concept of self-organization opens up further potential in dealing with dynamics and complexity in the system in the area of a dynamic and target-oriented structure formation and adaptation of organizational and management systems as well as a target-oriented integration of human workers in dynamic process environments. Nevertheless, it has to be assumed that the implementation of self-organized systems will be limited to sub-systems within the company, of which system behavior and interdependencies with other subsystems can be determined, mapped and modeled comprehensively [40]. A further research need has been identified, among other things, in the quantitative assessment of the potentials of the specific criteria and properties of the catalogue of criteria compared to the rather qualitative potential indications of the current catalogue of criteria. This quantification is necessary, in particular to be able to determine more precisely the limits of the positive effects of autonomous control and self-organization within specific logistic (sub-)systems with regard to the achievement of specific logistical goals to foster industrial applications.

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