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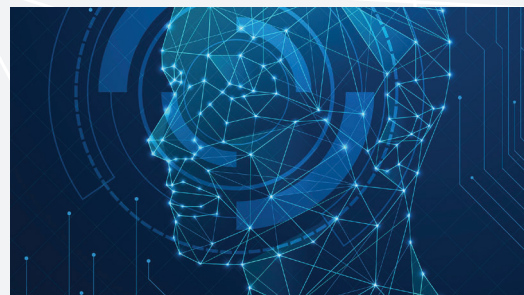


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Development of a Criteria Catalogue for the Classification of Intralogistics Systems in the Context of Self-Organization

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Abstract

The global demand for individualized products leading to decreasing production batch sizes requires innovative approaches how to organize production and logistics systems in a dynamic manner. Current material flow systems mainly rely on predefined system structures and processes, which result in a huge increase of complexity and effort for system and process changes to realize an optimized production and material provision of individualized products. Autonomous production and logistics entities in combination with intelligent products or logistic load carriers following the vision of the "Internet of Things" offer a promising solution for mastering this complexity based on autonomous, decentralized and target size-optimized decision making and structure formation without the need for predefined processes and central decision-making bodies. Customer orders are going to prioritize themselves and communicate directly with the required production and logistics resources. Bins containing the required materials are going to communicate with the conveyors or workers of the respective intralogistics system organizing and controlling the material flow to the autonomously selected workstation. A current research project is the development of a collaborative tugger train combining the potential of automation and human-robot collaboration in intralogistics. This tugger train is going to be integrated into a self-organized intralogistics scenario involving individualized customer orders (low to high batch sizes). To classify the application of self-organization within intralogistics systems, a criteria catalogue has been developed. The application of this criteria catalogue will be demonstrated on the example of a self-organization scenario involving the collaborative tugger train and an intelligent bin system.

Keywords

Self-organization, Intralogistics, Tugger train, Catalogue of Criteria

1 INTRODUCTION

Manufacturing companies are confronted with the increasing international competitive pressure, decreasing batch sizes due to a growing demand for individualized products and the requirement for the shortest possible delivery time [1]. Future logistics systems must enhance to adapt flexibly to the changing requirements of material flow in order to enable the factories of the future to produce personalized products in small batch sizes down to lot size one under the performance and cost conditions of today's mass production [2, 3]. The potential of evolutionary flexibilization of machine technology and production organization has already been largely exhausted. Through the networking, direct communication and collaboration of humans, machines and products aimed for in Industrie 4.0 the efficient production of individualized products will be supported through the concept of self-organization [4]. The market demand for economical production of individualized products at the cost conditions of mass production not only requires a changeable design of the factory environment, but also new methods how the production including the logistic processes are organized, planned and controlled [3].

As each product in this customized production differs from previous products in terms of the required

production processes as well as the required components and its flow through the factory, real-time configuration, control and decision-making within these flexible factory environments becomes a key challenge. For the organization, planning and control of flexible material flow systems within networked production environments, new methods and systems based on self-organized or autonomously controlled systems as well as the theory of the Internet of Things offer promising solutions. The approach of self-organized factory environments has been researched for a long time, e.g. in context with Fractal Factory structures [5]. In recent years, the topic has become increasingly important due to increasing market requirements on the one hand and the now available technical possibilities in the area of networking, decentralized information processing at the field level and the development of cyber-physical systems on the other [6]. According to Ten Hompel [3] and Günthner [7] this results in a configuration and regulation of the material flow at every point of the material flow system in order to keep pace with the increased flexibility requirements of production. Self-organized, autonomously controlled decentralized material flow control systems will distribute the required decision-making and control processes to intelligent logistical units [7]. Machines and objects like intelligent

products will jointly decide which tools and machines are to be used and with which conveying means components and (semi-finished) products are moving to the next production step. [8]

This paradigm shift requires profound organizational and control changes for companies, which may involve investments in new or adapted hardware and software components as well as product adaptations [9]. This required development in the direction of self-organized production systems will be evolutionary, since the investments in existing factories must first have paid off from the companies' point of view and a company-specific roadmap has to be developed for this transition [10].

2 SELF-ORGANIZATION

The theory of self-organized systems in combination with autonomous cooperation and control of logistic objects is seen as the answer for logistic systems to cope with complexity and dynamics [11]. A major aim of self-organization in logistics is to achieve changeable logistics systems. Nopper [12] describes the changeability of intralogistics systems as the "...capability of a material flow system [...] to adapt to the requirements of the environment beyond the limits of the system's design. In order to do so, the system must be expandable or adaptable. The requirements for material flow systems can be described along the dimensions of conveyed goods, layout and throughput."

2.1 Differentiation of self-management, self-organization and autonomous cooperation and control

Following Windt [11] the terms "self-organization" and "self-management" are to be distinguished as concretizations of the term "autonomous control". Even though the concepts of "autonomous cooperation", "self-organization" and "self-management" describe a system's ability to create order based on its own resources, there are differences regarding the form and degree of this ability [13]. *Self-management* as the broadest concept describes the fully autonomous development of a system involving the formulation of objectives and plans, the decision on its own organization forms and required resources [14]. *Self-organization* as an element of management outlines the manner how a system creates its own structure and processes by using its own abilities [15]. Self-organization is a long-established approach for human organizations and companies, for example investigated by Probst [16] in social systems and Warnecke [5] in context with the concept of Fractal Factories. *Autonomous cooperation* only refers to the freedom degree of system elements. So based on the current situation, the system elements are able to choose among given alternatives predefined by external entities like the company management [17].

The following definition of autonomous cooperation and control has been developed by the Cooperative

Research Centre (CRC) 637 "Autonomous Cooperating Logistic Processes – A paradigm Shift and its Limitations" at the University of Bremen [13]: "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. 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." According to Ten Hompel [18], the Internet of Things emerges within the framework of the self-organization and autonomous control of intelligent logistical objects. Within this Internet of Things logistical objects move independently through intralogistics networks like data packages in the Internet of Data. Ten Hompel [19] suggests to use the term "autonomous control", which was marked by the CRC 637, for logistics networks which has been mainly investigated within the CRC 637 and the terms "Internet of Things" and "self-organization" for intralogistics applications.

Regarding the characteristic features of self-organization and autonomous control, it can be observed that in the approach of self-organization, the characteristics at the management and organizational system level are more pronounced, whereas for autonomous control, the characteristics are more relevant for the execution system. In addition, the approach of autonomous control is more oriented towards the individual (logistical) object, while the approach of self-organization covers the system as a whole. In addition the approach of autonomous control is a more technology-oriented approach, e.g. in the discussion about Industrie 4.0 and the Internet of Things, since this approach is often associated with the use of new technologies whereas the approach of self-organization is more human focused. [11, 18, 20]

2.2 Characteristics of self-organized systems

Major characteristics that can be found in numerous self-organization approaches and definitions are the characteristics of complexity, dynamics, non-determinism, autonomy, redundancy, interaction and emergence. [13, 21, 22]

In addition, the considered systems are dynamic, complex systems no matter what type of system is involved in which discipline, since they are all based on the existence of numerous interrelationships between the system elements themselves and between the system and its environment [21, 23]. In the following, the major characteristics of self-organization in general will be discussed to set the theoretical base for self-organized intralogistics systems:

1. **Complexity:** A system is generally called a complex system, if its detailed description is hardly possible due to the variety of elements

and relations, even if all information and interactions would be known [24, 25]. The key difference between complicated and complex systems is the dynamics in the system. Complicated systems can consist of a large number of elements and connections, but these are subject to little movement or dynamics. Complex systems are characterized by a high dynamic that is present between the elements and can be described by the rate of change of the system over time. [24, 26]

2. **Dynamics:** Dynamics refers to the change of a system state or individual variables in a system in the time dimension. The intensity of the dynamics of the system processes depends in particular on the dynamics of the environment and the openness of the system to the environment. [27]
3. **Non-determinism:** A system is called non-deterministic if its behavior cannot be predicted over a longer period of time, although precise information about the states and rules of the system is available [13, 14]. The property of non-determinism should enable the system and its elements to deal more efficiently with complexity, dynamics and uncertainty in processes. [13, 28]
4. **Autonomy:** A major intrinsic feature of self-organized systems is the autonomy of the system in the sense that the relationships and interactions that unite the system only include the system itself and do not require further systems in the sense of a self-reference and operational coherence. This includes the self-design, control and development of the system, which is performed in a constant cycle of cause and effect. However, this does not lead to complete independence from other systems. No system that is part of a larger system can be completely independent or autonomous. It can only be autonomous with regard to certain criteria, as it can still be exposed to significant external influences or the environment, to which the system reacts using corresponding external signals. Thus, the concept of self-organization focuses on the active role of the system with its self-initiated actions, the design and influencing of system and environment as well as the formation and preservation of functional boundaries and identity. [16]
5. **Redundancy:** In a self-organized system, no distinction is made between the (active) organizing, designing or controlling components of the system and the (passive) components that are organized, designed or controlled. These capabilities are distributed across the system without the need for a hierarchy (heterarchy principle) and the potentials and mechanisms of system design and control are a characteristic of the system itself. The elements of the system take over the design and control of the system,

which have most of the information. This redundancy in the system means that several system components can be able to do the same (design and control). This redundancy of the functions also allows internal flexibility in the system. [16]

6. **Interaction and emergence:** The development of a self-organized structure in a system is based on the interaction of different system elements, which exchange information, substances, knowledge or energy with each other [21, 29]. Through the interaction of system elements new qualitative properties are formed within the system, which are called emergences [21] or synergetics [30]. These are based on the synergy effects of the elements in interaction with each other and cannot be related to individual system elements [21, 30]. The synergetics illustrates that the interaction of system elements makes the overall system more powerful than the mere sum of its subsystems [30].
7. **Autonomous order formation:** Through a higher degree of autonomy in the logistic system and its (intelligent) units a positive emergence and autonomous order formation can be achieved. In natural systems, completely autonomous order formation is generally possible, whereas in socio-technical systems, such as companies and logistics systems, autonomous control and self-organization can only take place to a limited extent following [21]. A major reason for this is that the origin and the system design of natural systems lie in the overall context of nature, which is generally self-organized. The creation and design of companies, in contrast, is a deliberately planned and artificially created existence by man, and thus externally organized [24].

With regard to intralogistics, it can be assumed that the optimal degree of self-organization in a complex logistics system in terms of achieving defined logistical goals does not correspond to the maximum degree of self-organization [31]. In this context, a combination of external and self-organization or the self-organization of selected functions or organizations within logistics systems, which are, however, subject to defined framework conditions or logistics values, is therefore regarded as appropriate [21]. So the determination of the feasible degree of self-organization to counter complexity and to achieve defined (logistic) goals is of crucial importance.

3 RESEARCH METHODOLOGY

To investigate the potential of intralogistics systems in the context of self-organization the research methodology of a reasoning cycle starting with the hypothesis formulation, deduction of predictions, testing and observation of predictions and induction/feedback into the initial hypothesis was applied (also see figure 1). The main hypothesis to

be proven is that self-organization applied, enables intralogistics systems to react more flexible and agile to changing system requirements.

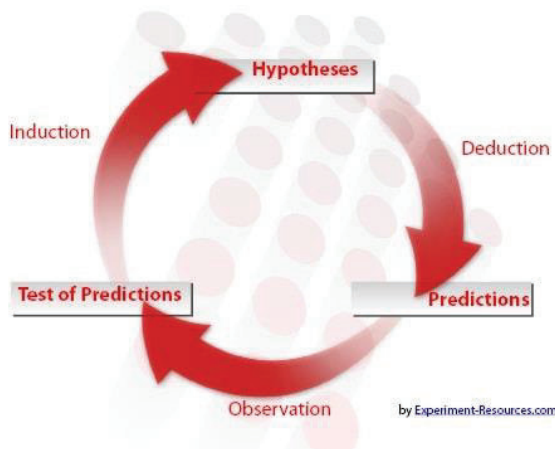


Figure 1 - research methodology of a reasoning cycle [32]

In order to do so a criteria catalogue was developed based on which the current degree of self-organization for intralogistics systems and the potentials for an increase can be determined. The catalogue was derived on the characteristics for self-organized systems with autonomous control according to Böse [33]. In addition, a generic model for intralogistics was developed which can be used to map different scenarios. Out of this generic model, scenarios were derived and then classified in the criteria catalogue developed.

4 RESULTS

4.1 Criteria catalogue

The criteria involves organizational as well as planning and control functions of intralogistics systems. To each criterion, different properties are assigned to cover the variety from conventional centralized controlled, external organized systems to autonomous controlled and self-organized systems. In order to operationalize the determination of the degree of self-organization a fulfilment value, which reaches from 0 (conventional external organized system) to 3 (entirely self-organized system), is allocated to every property of a criterion. To assess the degree of self-organization of a specific intralogistics system, all fulfilment values of the properties can be added up to the total fulfilment value. This total fulfilment value can be used to set the considered intralogistics system in relation to a completely self-organized system and so the degree of self-organization can be determined. The major criteria categories for the classification of the logistics systems are “decision making and organization”, “information processing” and “decision execution”. Within the category “decision making and organization” criteria such as the time behavior of the objective system, organizational structure as well as the change capability of the organization and role of

the human worker are assessed. The category “information processing” covers aspects as the location of data storage and processing. The third category of “decision execution” covers amongst others the system’s identification and measuring ability and flexibility.

4.2 Generic model

Following Böse [33] and Ropohl [34] the required system layers for a generic model of intralogistics are the decision, information and execution system level (also see figure 2). The decision system provides the decision-making ability. As mentioned before, in self-organized systems the decision-making functions are transferred to heterarchically organized logistic objects. The decision-making system also involves planning and control tasks enabling the system to develop and adapt in an autonomous, target-oriented manner. The information storing and processing ability on the information-processing layer forms the basis for the decision-making of the logistic objects interacting and exchanging information with each other. The decision execution layer deals with the decision execution ability of the logistic objects building up the intralogistics system consisting of sources, sinks and relations. These three layers set the basis for self-organization of intralogistics systems.

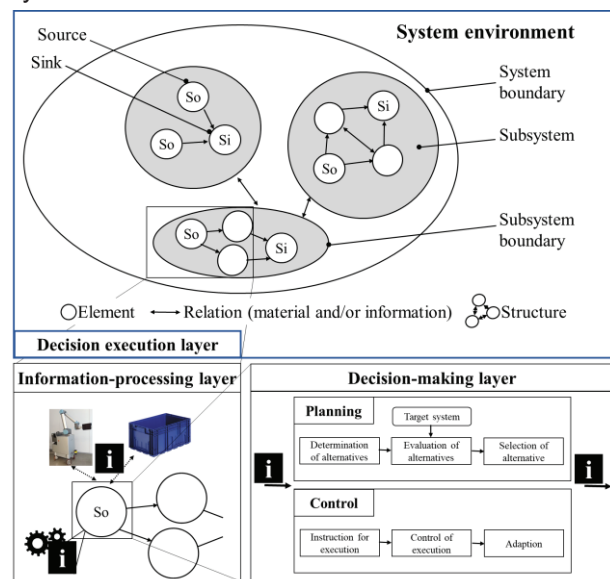


Figure 2 - Generic system model (cf.[33, 35])

4.3 Collaborative tugger train scenario

The following application scenario has been defined from the generic intralogistics model for a “Collaborative tugger train 4.0” and was classified in the criteria catalogue to visualize the existing degree of self-organization and thereby determine starting points for further enhancement. The aim of the collaborative tugger train 4.0 is to investigate the potentials of automation and human-robot collaboration for tugger train systems within changeable factory environments. The trailers of the tugger train are towed by an autonomous mobile

robot platform with an articulated robot on top of the platform to manipulate small load carriers (see figure 3). The robot platform of the tugger train system is capable to drive autonomously through changing factory environments and to handle bins by using different sensor systems. So in contrast to conventional tugger train systems no human worker is required to drive the tugger train and to load and unload the small load carriers.



Figure 3 - Collaborative tugger train

Based on the developed generic model described above a material provision scenario for an assembly environment has been developed. This scenario involves the collaborative tugger train system in combination with an intelligent bin system and other manual, semi-automated and automated conveyor systems to investigate the planning, design and control as well as the potential of self-organized intralogistics systems. The transport strategy for the tugger train is going to involve methods for flexible route planning, departure time determination, vehicle scheduling and order scheduling also considering previous research done by e.g. [36, 37].

Figure 4 shows an extract of the mapping of the scenario in the criteria catalogue (Initial scenario marked blue). The decision making and organization emergence are to be done in a decentralized manner based on the local target systems of the intelligent logistical objects. In this specific scenario, the intelligent bin might have the prioritized target to be transported as fast as possible from the source (supermarket storage) to the sink (workstation). The collaborative tugger in this scenario strives for maximum utilization of transport capacity. Therefore,

the tugger train is bidding on the transportation order of the intelligent bin by communicating the required transportation time to the intelligent bin. Besides the tugger train, also other transport systems of the intralogistics system, like roller conveyors or handcarts with a certain degree of intelligence, might bid on this transport in accordance with their target systems. The intelligent bin then compares all the bids coming from the transport systems and selects the most favorable transport. So an autonomous controlled material replenishment process can be initiated in a decentralized manner through a direct communication between the intelligent bin and available transport systems. The most relevant logistical objects as the transport systems and intelligent bins within the investigated system are uniquely identifiable and locatable leading to an overall medium degree of self-organization and autonomous control based on a scenario-specific total fulfillment value of 20 out of 42 with potential to increase. The maximum total fulfillment value of 42 represents in this case the maximum degree of self-organization for each criteria considered.

Criteria	criteria	Properties			
Decision making & Organization	Distribution of the target system	0	1	2	3
		global	mainly global	mainly local	local
	Adaptivity of the target system	0	1	2	3
		static	mainly static	mainly dynamic	dynamic
	organizational structure	0	1	2	3
		hierarchical	mainly hierarchical	mainly heterarchical	heterarchical
	Change capability of the organization	0	1	2	3
		low	medium	high	very high
	Number of decision alternatives	0	1	2	3
		None	some	many	unlimited
Information processing	Type of decision-making	0	1,5		3
		extrinsic (static)	intrinsic (rule-based)		Intrinsic (learning)
	Place of decision-making	0	1,5		3
		system level	subsystem level		system element level
Decision execution	Human role	0	1	2	3
		passive, executing	mainly passive, co-decise	mainly active, co-decise	Actively decisive
	Predictability of system/ element behavior	0	1	2	3
		Elements and system deterministic	Elements non-/system deterministic	System non-/elements deterministic	Elements and system non-deterministic
Information processing	Location of data storage	0	1	2	3
		central	mainly central	mainly decentralized	decentralized
Decision execution	Location of data processing	0	1	2	3
		central	mainly central	mainly decentralized	decentralized
Decision execution	Flexibility	0	1	2	3
		inflexible	little flexibility	flexible	very flexible
	Identifiability	0	1	2	3
Decision execution		no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable
	Localizability	0	1	2	3
		no elements can be localized	some elements can be localized	many elements can be localized	All elements can be localized
Increasing degree of self-organization					

Figure 4 - Self-organized tugger train scenario mapped in catalogue of criteria (cf. [33, 38])

To increase the degree of self-organization of the tugger train system among other things the capabilities of all logistic objects (bins, tugger train, etc.) have to be further increased in the field of decentralized, intrinsic decision making,

decentralized data storage and processing as well as identification and localization capabilities (Potential marked green in figure 4). Also a more active integration of the human worker, e.g. in the sense of a higher integration and responsibility for the intralogistics system, offers potential to increase the level of self-organization. By doing this, the target-oriented, autonomous organization of the intralogistics system involving the tugger train system and other intelligent logistic objects can be further improved.

5 CONCLUSION AND OUTLOOK

One of the next steps will be the implementation of the developed scenario to investigate the intralogistics system behavior in combination with changing production system requirements. First will be the implementation of the described collaborative tugger train scenario with a medium level of self-organization in the ESB Logistics Learning Factory at Reutlingen University. In line with the selected research method of the reasoning cycle the hypothesis that self-organization enables intralogistics systems to react more flexible and agile to changing system requirements will be tested. Based on the observations of this testing, a scenario with a higher degree of self-organization is going to be defined by applying the developed generic intralogistics model and classifying of the developed scenario in the criteria catalogue. Then the results of these scenarios are going to be compared with each other with respect to the logistic goal achievement and fulfillment of the hypothesis. Further scenarios with different intralogistics infrastructure will be defined, implemented and analyzed in context of self-organization and autonomous control in order to develop a method for the autonomous control of changeable, hybrid logistics systems in the end.

6 ACKNOWLEDGMENTS

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