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Self-organization of changeable intralogistics systems at the ESB Logistics Learning Factory

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Abstract

The persistent development towards decreasing batch sizes due to an ongoing product individualization, as well as increasingly dynamic market and competitive conditions lead to new changeability requirements in production environments. Since each of the individualized products might require different base materials or components and manufacturing resources, the paths of the products going through the factory as well as the required internal transport and material supply processes are going to differ for every product. Conventional planning and control systems, which rely on predefined processes and central decision-making, are not capable to deal with the arising system's complexity along the dimensions of changing goods, layouts and throughput requirements. The concepts of "self-organization" in combination with "autonomous control" provide promising solutions to solve these new requirements by using among other things the potential of autonomous, decentralized and target-optimized decision-making. A major enabler for the development towards autonomous changeable intralogistics systems are intelligent logistical objects (e.g. smart products, bins and conveyor systems) which are able to communicate and interact with each other as well as with human workers. To investigate the potential of automation and human-robot collaboration for intralogistics, a research project for the development of a collaborative tugger train has been started at the ESB Logistics Learning Factory in line with various student projects in neighboring research areas. This collaborative tugger train system in combination with other manual (e.g. handcarts) and (semi-)automated conveyor systems (e.g. automated guided forklift) will be integrated into a dynamic, self-organized scenario with varying production batch sizes to develop a method for target-oriented self-organization and autonomous control of intralogistics systems. For a structured investigation of self-organized scenarios a generic intralogistics model as well as a criteria catalogue has been developed. The ESB Logistics Learning will serve as a practice-oriented research, validation and demonstration environment for these purposes.

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Keywords: Self-organization; Autonomous control; Intralogistics; Learnung Factory

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1. Introduction

In order to be able to compete, companies must be able to deliver as quickly and cost-effectively as possible on time. In addition, shorter product life cycles, decreasing batch sizes and an increasing variety and complexity of products and processes are among the central challenges of production and logistics [1, 2]. The increasing complexity in companies and their environment leads to a constantly growing scope of coordination and a rising coordination intensity and dynamics of logistic processes. On the one hand, the increasing complexity requires more and more time for problem analysis and decision making, while on the other hand, the available reaction time is decreasing [3]. Therefore, companies have to make their production systems more flexible and changeable in order to be able to react quickly and cost-effectively to changes [4]. A central requirement of future logistics networks is consequently the ability to adapt to changing conditions. This not only affects the (changeable) design and planning of logistics processes, but also the infrastructure used, which must be adaptable in future [5]. According to experts, swarms of autonomous vehicles that learn from each other, negotiate orders and rights of way with each other and exchange position information will dominate intralogistics transport systems to face these new changeability requirements [4–6]. In line with this development, logistics objects like shelves and bins will become more intelligent and will be able to take over tasks as inventory management, monitoring of minimum stocks, order replenishment based on a close interaction with other intelligent objects within the (logistics) system [5].

2. Self-organization of changeable material flow systems

2.1. Flexibility and Changeability

From a systems-theoretical point of view, flexibility is required to cope with complexity and dynamics [8]. According to Kuzmany [9] a flexible material flow system must be able to transport products with any dimensions and weights (material flexibility), to reach or serve any location in the factory (layout flexibility) and to adapt to changing production output requirements (throughput flexibility). Flexible material flow systems, however, are only able to react to requirements that have already been taken into account in planning. Changeability, on the other hand, offers the possibility of extending and changing a system beyond previously planned boundaries. The changeability or adaptability therefore corresponds to an extension of flexibility in order to be able to react to unplanned events [10]. Only through the extensibility of the material flow system, e.g. by adding further vehicles to the system, and integration capability, e.g. by combining different material flow systems, the set limits can be overcome and reactions to unplanned changes can be realized (strategic changeability) [11, 12]. For the organization, planning and control of changeable 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 [5].

2.2. Self-organization of intralogistics systems

The approach of self-organized factory environments has been researched for a long time, e.g. in context with Fractal Factory structures [13]. The interdisciplinary understanding of self-organization is supplemented from an engineering point of view by the concept of autonomous control. Significant differences are difficult to identify when comparing the characteristics like decentralized decision-making, emergence, non-determinism and heterogeneity, as these largely apply to autonomous control and self-organization. Nevertheless, in the autonomous control approach the characteristics and capabilities are more pronounced at the level of the execution system (material flow and logistics), whereas in the self-organization approach the characteristics and capabilities are more evident at the level of the management and organization system. In addition, the concept of autonomous control is more focused on the individual (technical) objects whereas for the approach of self-organization a dynamic structure formation, the preservation of the overall system stability and the integration of humans is of high importance [1]. In natural systems, a completely autonomous order formation is generally possible, while in socio-technical systems, such as companies, this can only take place to a limited extent [8]. In practice, an interplay of externally and self-organized processes in living organizations has proven itself. For example the prerequisites and initial conditions within an organization might be externally defined by the management or supervisors to make the system more stable, while the potentials of self-organization are applied for the processes in the executing system to cope with dynamic changes [13]. In intralogistics the approach of self-organization aims on the creation of changeable logistics structures based on an effective and efficient coupling of logistics systems or objects, such as transport systems and load carriers, as well as human workers in line with changing (logistical) requirements [3]. To achieve a dynamic configuration of the intralogistics system in accordance with changing requirements of the manufacturing system, the potentials of autonomous control on the execution level and self-organization on the management and organizational level have to be combined in a synergetic way. Investigations of Scholz-Reiter et al. [14] showed that the optimal degree of autonomous control in complex logistics systems does not correspond to the maximum degree of autonomous control. Therefore, for a given level of complexity, the logistic goal achievement increases with an increasing level of autonomous control, reaches an optimum and then drops again. Consequently, a major challenge and research gap is to find the target-value-optimized degree of self-organization and autonomous control for changing production scenarios involving human workers as well as intelligent infrastructure components.

3. Self-organization of intralogistics at ESB Logistics Learning Factory

Learning factories, such as the ESB Logistics Learning Factory (LLF) at the ESB Business School (Reutlingen University), covering a real value chain and product have proven to be an ideal environment for teaching and training as well as for the development and demonstration of future-oriented production scenarios [15, 16]. In addition, learning factories allow innovative approaches or solutions to be tested without the risk of loss of revenue and at the same time students, researchers as well as industrial partners can be involved for education, research, training and transfer into industrial practice. At the LLF various research projects (e.g. development of a collaborative tugger train system) and student projects (e.g. development of a modular intelligent bin system) dealing with different aspects of changeable, self-organized intralogistics systems in context with varying production batch sizes and individualized products are currently running. A major aim of these research activities is to investigate the potentials and limitations of self-organization and autonomous control in intralogistics.

3.1. Holistic approach

To investigate the potential of self-organization for intralogistics systems 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 is applied. The main hypothesis to be proven is that self-organization applied, enables intralogistics systems to react more flexible and agile to changing system requirements. To determine the current degree of self-organization for intralogistics systems and potentials for an increase, a criteria catalogue has been developed. The catalogue was developed based on the characteristics for self-organized systems with autonomous control according to Böse [17] and covers organizational as well as planning and control functions of intralogistics systems. The potentials, which can be achieved by an increase of the degree of self-organization have been determined based on a literature research and have been allocated to the properties of the criteria catalogue. To cover the variety from conventional centralized controlled, external organized systems to autonomous controlled and self-organized systems specific properties have been assigned to each criterion. To simplify 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. Thereby all fulfilment values of the respective properties can be added up to the total fulfilment value to assess the degree of self-organization of a specific intralogistics system and to compare it with other systems or system alternatives. The main criteria categories of the criteria catalogue are “decision making and organization”, “information processing” and “decision execution”. The category “decision making and organization” involves criteria such as the time behavior of the target system, organizational structure as well as the change capability of the organization and role of the human worker in the system. The second category “information processing” deals with aspects as the location of data storage and processing and the interaction capabilities of the logistic objects. The third category of “decision execution” covers amongst others the system’s identification and measuring ability as well as the flexibility of the analyzed system. In addition, a generic model for intralogistics has been developed which can be used to map different scenarios. Following Böse [17] and Ropohl [18] the required system layers for a generic model of intralogistics are the decision-making, information-processing and decision-execution system level which also correspond to the covered categories of the criteria catalogue. More details about the developed criteria catalogue and the generic model for intralogistics can be found in [19].

3.2. Self-organized, autonomous controlled collaborative tugger train scenario

The following application scenario has been defined from the generic intralogistics model for the research project “Collaborative tugger train 4.0” which is running at the LLF. This application scenario has been classified in the criteria catalogue to visualize the existing degree of self-organization and thereby determine starting points and potentials 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 1). The robot platform of the tugger train system is capable to drive autonomously through changeable 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.

Based on the developed generic model mentioned above a material provision scenario for the LLF 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 of the LLF 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. [20, 21]. Figure 1 shows an extract of the mapping of the scenario in the criteria catalogue (Initial scenario marked blue). The decision-making and organization emergence will be done in a decentralized manner based on 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 manual 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 option. So an autonomous controlled, self-organized material replenishment process can be initiated in a decentralized manner through a direct communication between the intelligent bin and available transport systems. This facilitates a flexible and target-oriented response to short-term, dynamic changes in the assembly and logistics system. In this scenario, the most relevant logistical objects as the transport systems and intelligent bins within the investigated system of the LLF are uniquely identifiable and locatable which supports the self-organized (re-)structuring of the logistics system. This leads to an overall medium degree of self-organization and autonomous control based on a scenario-specific total fulfillment value of 22 out of 51 with potential to increase. The maximum total fulfillment value of 51 represents in this case the maximum degree of self-organization for each criteria considered.

a

Criteria category	criteria	Properties			
Decision making & Organization	Validity of the target system	0 long term	1,5 medium term		3 short term
	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
	organizational structure	0 hierarchical	1 mainly hierarchical	2 mainly heterarchical	3 heterarchical
	Change capability of the organization	0 low	1,5 medium		3 very high
	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	1,5 Active with defined scope of action		3 Actively decisive
	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
	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
	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

Increasing degree of self-organization →

b

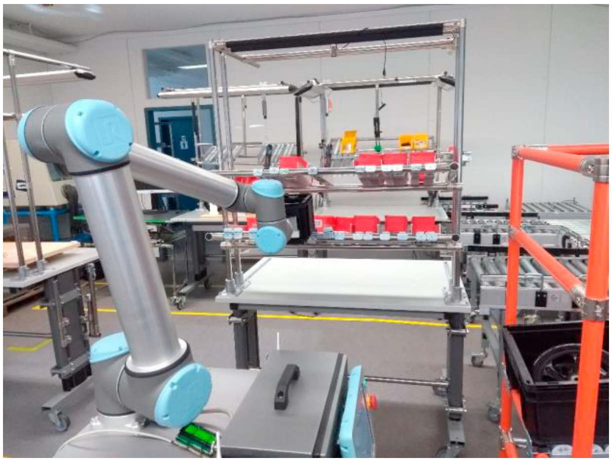

Fig. 1. (a) Extract of criteria catalogue; (b) image of collaborative tugger train system in the LLF.

According to the potentials allocated to the criteria and properties in the criteria catalogue, an increase of the degree of self-organization can lead e.g. to a further improvement of measurable metrics (e.g. lead times) as well as non-quantifiable metrics (e.g. flexibility and robustness of the system). To increase the degree of self-organization of the tugger train scenario 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 1). 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 and to improve the overall system performance. Thereby the target-oriented, autonomous organization of the intralogistics system involving the tugger train system and other intelligent logistic objects can be further improved in line with changeable (production) system requirements. For the realization and investigation of these scenarios, the LLF will serve as a research, validation and demonstration environment integrating students, researchers as well as industrial partners. In addition, the learning factory concept is not only applied to make the student education more practice-oriented (e.g. based on hands-on trainings and demonstrations) in the field of changeable intralogistics and production environments. Besides this, students are also involved in the further development and implementation of these innovative approaches and solutions, e.g. based on specific semester projects or final year projects.

4. Conclusion

The approach of self-organized, autonomous control for intralogistics bears a huge potential to solve the arising challenges in context with decreasing batch sizes, increasing international competition and the increase of complexity by shifting some of the decision-making power to intelligent objects on the shopfloor level. One of the next steps will be the implementation of the described scenario in the LLF to investigate the intralogistics system behavior in combination with changing production system requirements. 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, further scenarios with different intralogistics infrastructure and solution alternatives will be defined, implemented and analyzed to investigate the potentials and limitations of self-organization and autonomous control. These findings will be then incorporated into the development of a method for the autonomous control of changeable logistics systems.

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