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Self-organization and autonomous control of intralogistics systems in line with versatile production at Werk150

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Abstract

The planning and control of intralogistics systems in line with versatile production systems of smart factories requires new approaches and methods to cope with changing requirements within future factories. The planning of intralogistics can no longer follow a static, sequential approach as in the past since the planning assumptions are going to change in a high frequency. Reasons for these constant changes are amongst others external turbulences like rapidly changing market conditions, decreasing batch sizes down to customer-specific products with a batch size of one and on the other hand internal turbulences (like production and logistic resource breakdowns) affecting the production system. This paper gives an insight into research approaches and results how capabilities of intelligent logistical objects (intelligent bins, autonomous transport systems etc.) can be used to achieve a self-organized, cost and performance optimized intralogistics system with autonomously controlled process execution within versatile production environments. A first consistent method has been developed which has been validated and implemented within a scenario at the pilot factory Werk150 at the ESB Business School (Reutlingen University). Based on the incoming production orders, the method of the Extended Profitability Appraisal (EPA) covering the work system value to define the most effective work system for order fulfilment is applied. To derive the appropriate intralogistics processes, an autonomous control method involving principles of decentralized and target-oriented decision-making (e.g. intelligent bins are interacting with autonomously controlled transport systems to fulfil material orders of assembly workstations) has been developed and applied to achieve a target-optimized process execution. The results of the first stage research using predefined material sources and sinks described in this paper is going to set the basis for the further development of a self-organized and autonomously controlled method for intralogistics systems considering dynamic source and sink relations. By allowing dynamic shifts of production orders in the sense of dynamic source and sink relations the cost and performance aims of the intralogistics system can be directly aligned with the aims of the entire versatile production system in the sense of self-organized and autonomously controlled systems.

Keywords

Intralogistics; Autonomous Control; Self-organization; Decentralized decision-making;

1. Introduction

Companies are increasingly confronted with growing international competitive pressure, decreasing batch sizes due to a rising demand for individualized products as well as the demand for the shortest possible delivery time [1,2]. In order to enable the factories to produce personalized products in small batch sizes down to a batch size of "1" under the performance and cost conditions of mass production, logistics systems must be able to adapt flexibly to changing requirements of the material flow [3,4]. Therefore a versatile behavior of the production and logistics system in the sense of an early or proactive adjustment of objects, structures and processes of value creation is crucial. The trigger of a required adaption of production systems are internal and external turbulences. The term “turbulence” stands for the effects of mostly unexpected changes which are acting from the outside or within a company [5]. A distinction is made between internal and external turbulences. Internal turbulences are having their origin in changes within the production system, like machine breakdowns or new product variants, whereas external turbulences are arising due to reasons of the outside of the company like changing market conditions or delayed deliveries of suppliers [6]. As each product in a customized production with various potential turbulences 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, the real-time configuration, control and decision making is a central challenge. Self-organized, autonomous controlled material flow systems will distribute the necessary decision-making and control processes among intelligent logistics units [7]. Machines and other objects in production will jointly decide on the used tools and machines in close cooperation with autonomous transport systems deciding on the transport of components and (semi-finished) products from their current location to the next production step.

2. Research design

To investigate the potential of self-organization and autonomous control for an improved target achievement within intralogistics systems the research methodology of a reasoning cycle has been chosen. The reasoning cycle starts with the hypothesis formulation and continues with the deduction of predictions, testing and observation of predictions and induction/feedback into the initial hypothesis [8]. The main hypothesis to be proven is that the application of self-organization and autonomous control leads to an improved achievement of cost and performance goals within versatile production systems. To prove this hypothesis a two-step approach is followed. In the first step, a first approximation based on fixed material sources and sinks in the work system is investigated. The second step will be the investigation of the application of self-organization and autonomous control within production systems with flexible material sources and sinks for an integrated and simultaneous cost and performance optimization of all production and logistics resources.

3. Self-organization and autonomous control

In general, the concept of self-organization deals with the explanation of the autonomous emergence of ordered structures in open, interacting, non-deterministic, dynamic-complex systems. In addition, the approach of self-organized systems is focused on how a system designs its processes and systematic structures in an autonomous manner. The concept of autonomous control generally describes processes of decentralized decision-making in non-hierarchical (heterarchical) structures based on interacting elements in non-deterministic systems with autonomous decision-making capabilities. Autonomous controls aims on achieving a higher robustness and positive emergence of the overall system through a distributed, flexible management of dynamics and complexity arising in the system. [9]

Although the concepts of self-organization and autonomous control have many common characteristic features, the approach of self-organization is more focused to the management and organizational level of holistic systems whereas the approach of autonomous control is more evident at the execution level and single object level of systems. For a more detailed characteristics-based differentiation of autonomous control and self-organization, please also see Windt [9] and Schuhmacher [10]. The ability of self-organized systems to change the system’s structure or processes requires in particular the timely recognition of a need for change (e.g. due to external or internal turbulences) and the rapid planning and implementation of the necessary change in industrial management. Therefore, it is essential to master the planning complexity, which can be reduced by decentralized control systems. A major task of the company’s management is to define guidelines and decision corridors for the decentralized initiation and control of change within the company. In this way, autonomous control can evolve from the local level such as such as the intralogistics system to the target-oriented self-organization of the entire company [11]. Based on the self-organization capabilities of the production system in conjunction with an appropriate visualization application, the plant manager or corresponding specialist worker gains a real-time overview of production for decision support and can react quickly to complications in order to make well-founded decisions for adjustments within the production system. [12]

In addition decision-making within technical systems will no longer be possible through hierarchical structures following the classical automation pyramid, since a large number of decisions for the control of the material flow must be made in near-realtime and a predefined, target size-optimized solution cannot be predefined centrally for every eventuality. Instead, these tasks will be performed in a decentralized manner by the intelligent objects in the material flow system, such as the transport units, transport vehicles and software agents. Thus, according to Hompel [11] it can be stated that with an increasing complexity of logistics systems the degree of decentralization and self-organization must increase in order to be able to control them. [11][7]

4. First approximation for versatile logistics

As a first step before the development of an entirely self-organized and autonomous control method for a holistic consideration of logistics and production goals within versatile production environments, a first approximation using a two-step approach for the sequential optimization of the value creation system and the autonomously controlled intralogistics system has been used (see Figure 1). Therefore two separate equation systems for the optimization of the value creation system (consisting of assembly, production and work system-related storage resources) and for the autonomously controlled, versatile logistics system (consisting of transport systems) have been set up covering the cost and performance measures of these systems. To derive the most effective work system to fulfill the incoming small batch size production orders in line with the set targets (cost, performance and qualitative goals) of the work system, the method of the Extended Profitability Appraisal (EPA) has been applied at the pilot factory Werk150. Based on the cost calculations and determination of the work system values of different work system alternatives which are covered by the EPA, the value creation system with an optimized target achievement for changing production system requirements can be determined. Building blocks for the definition and calculations of the work system alternatives, further referred as value creation system to distinguish it from the logistic transport systems, are the locations of value creation (LVC) which are representing value adding production resources as workstations or machines and the locations of storage (LOS) for buffer storages in the production system. The result of the EPA is the definition of the target-optimized value creation system including the required material flow relations. After the determination of the most target-oriented work system configuration, the work system will be implemented and the developed autonomous control method will be adjusted to the new optimized layout and the defined material sources and sinks of the value creation system. The transport order allocation is than entirely done in an autonomous, target oriented manner following the defined optimization equation for cost and performance calculations of all available transport system (TS) of the logistics system to achieve a target system-optimized logistical process execution also in case of arising turbulences. In case of target-system changes or deviations from the defined target values (e.g. due to changed products or production numbers), the procedure of the EPA can be (manually) initiated again by the production manager to change the structural formation of the value creation system. This separate consideration of production and logistics targets and manual triggering of the restructuring processes is a pre-stage to a fully autonomous self-organized work system behavior, in which the need for a restructuring would have to be detected and initiated autonomously and the targets of production and logistics are considered simultaneously based on adaptable source and sink relations in the production system (second step following the chosen research design).

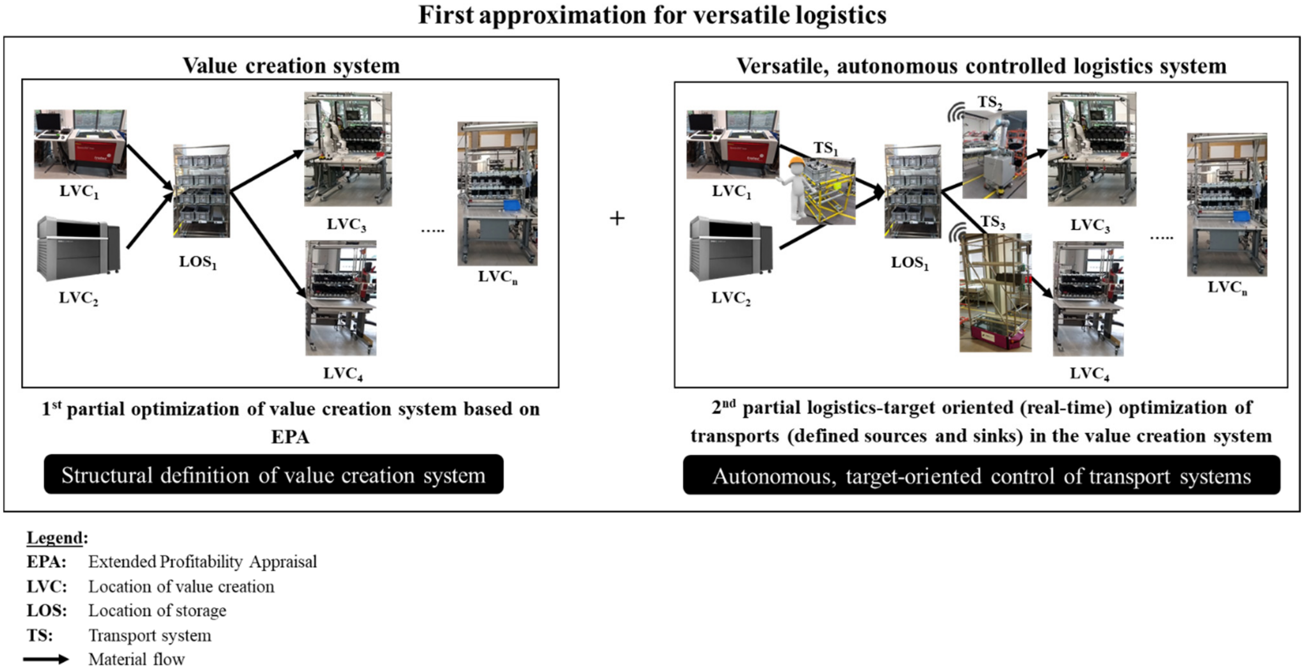

Figure 1: First approximation for versatile logistics with fixed sources and sinks

4.1 Extended Profitability Appraisal

The EPA procedure has been developed and tested during the Federal German government's program for Humanization of Working Life (HdA - Humanisierung des Arbeitslebens) in collaboration of employers' associations, trade unions and researchers in the 1980s [13]. The conventional methods of profitability and investment calculation are limited to the measurement of the profitability of technical investments and directly quantifiable monetary data as expenditures for technology, operating resources and personnel as well as estimated revenues. Important indirect monetary data such as the reduction of machine downtimes, increased flexibility of the work system, absenteeism and scrap costs for the monetarization and operationalization of these objectives is not taken into account in conventional of profitability and investment calculation methods [14,13]. For the development and comparison of different work system alternatives and the assurance of a high planning quality and acceptance of work system redesign activities, the integration and contribution of experienced employees with specific knowledge from different functional areas is of decisive importance. The EPA procedure differs significantly from conventional methods of profitability calculation by a holistic consideration of economic factors such as costs and performance as well as technical, organizational and personnel factors (work system value). The EPA is therefore divided into the two subsections of the economic efficiency comparison and the work system value determination. The determination of the work system value covers factors and aspects which can hardly or not at all be assessed monetary, whereas the economic efficiency comparison section covers purely monetary factors. At the end of the EPA both sub-ratings are summarized in a joint presentation of the results [14]. An overview of various diagnosis-oriented and decision-oriented EPA procedures can be found in [15].

Besides the method of the work system determination, the method of an argumentative balance sheet can be applied to assess monetary hard to quantify evaluation criteria. This balance sheet is used to list advantages and disadvantages in the spheres of "Effects on the production system itself" and "Effects of a system implementation regarding customer markets, customers and suppliers". The argumentative balance sheet is a pure collection of arguments on advantages and disadvantages without any ranking possibilities of alternative work system alternatives, therefore it can be only seen as an addition to the work system value determination. The method of work system value determination uses the method of cost-benefit analysis and is particularly well suited for the evaluation of work system alternatives [14]. The result of the work system value determination also provides starting points regarding strengths and weaknesses of different work system configurations. By a combination of advantages of single solutions from different investigated work system alternatives, a target-oriented work system solution can be determined iteratively via various runs of the work system value determination procedure.

For the developed and applied method the procedure of Bullinger [14] is applied to determine the work system values (WSV) of different possible work system alternatives (also see Figure 2). The WSV determination procedure starts with the selection and definition of the evaluation criteria based on the non-monetary and/or hard to quantify targets which have to be fulfilled by the work system. The weighting of the evaluation criteria in the next step is done by a pairwise comparison to calculate the weighting factors of each criteria. The third step covers the determination of the fulfilment factors for every criterion and work system alternative. The determination of the fulfilment values is done with a table matrix containing all work system planning alternatives and evaluation criteria. The fulfilment of each criteria is estimated by an expert team based on a point scale from 0 (Criteria is not fulfilled) to 10 (Criteria is fulfilled) for each work system alternative after the other. The calculation of the work system value for each alternative is done by multiplying all the fulfilment factors with the (normalized) weighting factors for every criterion and adding up all the sub values resulting in the work system value for each planning alternative. The last step of the WSV determination is the evaluation, identification of the work system with the highest WSV and presentation of the results, e.g. via bar chart visualizations for a simplified comparison and interpretation of the analysis results.

Work system value determination	
Step 1	Selection and definition of evaluation criteria
Step 2	Weighting of the evaluation criteria
Step 3	Determination of fulfilment factors per criterion and alternative
Step 4	Work system value calculation
Step 5	Evaluation and presentation of results

Figure 2: Procedure for work system value determination (cf. [14])

4.2 Autonomous control method

Autonomous control of logistical processes is given when the logistical object itself processes information, makes decisions and executes them [9] [16]. The autonomous decision making and behavior in general of intelligent logistical objects interacting with each other has to follow defined goals to achieve the desired effectiveness and efficiency of the production system. The general goals of production logistics following Wiendahl [17] are set by a maximization of logistics performance in form of a close adherence to delivery dates and short throughput respectively delivery times as well as a minimization of logistics cost represented by capital commitment costs and a high utilization. The cost and performance goals of specific intelligent logistic objects as transport systems, transport units and services have to be defined and matched with their (logistic) function to achieve the required target-oriented object behavior within the production system. In the sense of self-organized systems, these targets as well as the systems elements and structure will change over the time to maintain a viable, effective and efficient (production) system [18,19]. Based on the selected work system/value creation system configuration determined by the EPA, the target systems (e.g. targets and prioritization) of the intelligent objects have to be adjusted to the respective production system needs which are linked to the evaluation criteria used for the WSV. For example, the goal of a higher logistics performance can be dynamically prioritized higher than logistics costs in the target systems of the logistics objects in production scenarios involving peaks in customer orders to achieve shorter lead times in the production system. The results of the implementation and validation of the developed first approximation method within a scenario at the pilot factory Werk150 for a target-oriented configuration of work systems in combination with an autonomous control method for a versatile intralogistics system behavior will be described in the following.

5. Validation Scenario at pilot factory Werk150

Pilot factory Werk150 is a close-to-reality research, education and training environment at ESB Business School (Reutlingen University). Learning factories, such as the Werk150, covering a real value chain and product have proven to be an ideal environment for the development and demonstration of future production scenarios [20]. Holistic learning factories, like Werk150, are especially suitable for complex research topics like the industry-oriented development of self-organization and autonomous control methods since state-of-the-art industry infrastructure is available and at the same time, production downtimes within the learning factories do not lead to any financial losses. So for testing and validation of the developed first approximation for a cost and performance optimized value creation system configuration and target-system oriented autonomously controlled logistics process execution, a versatile production scenario involving different product-mixes, production numbers as well as new products has been defined.

5.1 Selection of target-optimized work system setup

Based on the incoming production orders and defined strategic goals of the pilot factory Werk150, the EPA method covering economic efficiency comparisons and work system value (WSV) determinations for qualitative factors which can hardly be assessed monetary has been applied to define the most effective work system for order fulfilment in a versatile production scenario. For the WSV determination the procedure described in section 4.1 has been followed. In the first step, the evaluation criteria for the work system alternatives has been selected and defined to cover the requirements of versatile production systems with changing production volumes, models mixes and turbulences like production and logistics resource breakdowns as well as rush orders. Amongst others, the adaptability to volume fluctuations, sensitivity to resource failure and flexibility regarding process changes have been considered. Afterwards the weighting factors of each criterion has been calculated by applying the method of pairwise comparison.

In the next step different work system alternatives defining the assembly system (e.g. individual workstations doing all required assembly steps, assembly lines with a division of tasks,…) as well as the logistics system (e.g. pre-picking of customer individual product parts and delivery to dynamically selected assembly station vs. provision of all parts at the workstation) have been developed and the fulfillment factors per weighted criterion and alternative has been determined by a group of students and researchers. Next, the WSV and cost and performance values of the different work system alternatives have been calculated. The process steps of defining work system alternatives and calculating the WSV and cost and performance values based on the developed equation system of the value creation system has been repeated based on the results of the first runs to generate the target-optimized work system solution which is shown in Figure 3.

Figure 3: Target-optimized work system solution at Werk150

The assembly system consists of six assembly work stations of which two workstations can each carry out the same assembly steps (but with different tools or collaborative robots) to achieve a high flexibility regarding changing product variants as well workstation failures. The workstations are on wheels and therefore moveable to change the assembly system layout e.g. into an assembly line to maximize output for higher batch production batch sizes. At all assembly workstations, only the required standard components or C-parts are kept in large quantities, all customer-specific components are either delivered pre-picked or delivered directly to the corresponding assembly workstation. The pre-picking is done at human-robot-collaboration workstations (see right below in Figure 3) for the scooter which is the multi-variant base product assembled at Werk150. The pre-picked components are directly placed by the robots as well as the human pickers on fixtures which are used for transport as well as for assembly purposes at the workstations. The pre-picked components are then transported from the picking workstations by a modular, decentrally controlled roller conveyor to a transfer point at the end of the roller conveyor system from where the scooter components are transported to the next workstation with free work capacity based on an autonomous control method for a target-oriented selection of the transport system (manual, semi-automated/collaborative, fully automated transport system).

5.2 Autonomous control of transport orders

As a first preliminary stage before a completely self-organized intralogistics scenario, the transport orders in the scenario described above are coming with predefined material sources and sinks (workstation with least remaining work) to test and validate the developed autonomous control method for a cost and performance optimized transport order allocation involving various alternative transport systems. The target measures to achieve economic efficiency by the selection of the appropriate transport systems within this method have been derived from [17] [21] and operationalized for the desired transport order allocation application. The logistics performance is measured by the target value of the adherence to schedule (deviation to due date of delivery) and transportation and waiting times. The logistics cost dimension is measured based on the transport system-related process costs aiming on a high capacity utilization. These performance and cost target dimensions are considered by the transport systems as well as the (intelligent) bins and transport units for close-to-real-time decision-making and execution of material transports. For example, if a bin with c-parts or a fixture with pre-picked scooter components has to be transported from its current location to a specific workstation, the intelligent transport unit (or in case of non-intelligent transport units the transport client) communicates directly with the transport systems of the work system at Werk150. The transport systems are then responding to this enquiry with their specific cost and performance values to fulfill the transport. In case of manual transport systems involving a human worker the enquiry is handled via a self-developed logistics worker client app, which keeps track of open, denied and accepted transport orders and also gives the worker the possibility to manually accept and reject transport orders. The transport unit or intelligent bin as the customer within this processes, then decides on the most favorable transport offer according to its target measures and communicates the decision to the transport systems. In addition to conventional automated guided vehicles, semi-automated transport systems (e.g. electric pallet trucks) as well as manual transport systems (e.g. human workers, handcarts) this autonomous control method is also applied for a collaborative tugger train system. In contrast to conventional tugger train systems which are driven by a human worker and also the manipulation of the goods is done by a human, this tugger train system is able to drive and manipulate goods autonomously without the need for predefined transport routes or transport schedules. The tugger train system consists of an autonomous robot platform which is towing the trailers of the tugger train. On top of the robot platform, a collaborative robot is mounted to pick small load carriers from shelves, place them on the trailers and unload them at the respective work stations. So the benefits of tugger train systems, like the possibility to fulfill high volume transport orders, can be combined with the potentials of autonomous controlled material flow systems.

A simulation study of this autonomous control method has already proven an increased target achievement of transport system related cost and performance goals for versatile production environments with turbulences (like breakdowns of transport systems). The simulation showed amongst others a lead time reduction of up to 30 % as well as significant improvements of the utilization of the transport systems and the adherence to schedule (also see Grosse-Erdmann [22 – to be published]). First practical tests of the autonomous control method described above involving an autonomous robot transport system and an autonomous collaborative tugger train system of the project "Collaborative tugger train 4.0" have already shown similar results in combination with the EPA of the first approximation for versatile logistics. Although the benefits considering costs and performance have shown to be especially significant in factory scenarios with arising internal turbulences like transport system breakdowns or unplanned rush orders which have to be fulfilled.

When the monitored cost and performance measures of the logistics system and/or the assembly system are falling below defined limits, the EPA procedure is restarted to restore a target-oriented work system configuration as described in section 4.1 following. This process starts again with the economic efficiency comparisons and the WSV determinations for different value creation system alternatives based on the incoming production orders and defined work system goals. After the determination of the work system alternative with the highest target fulfillment, the target systems of intelligent logistical objects are adjusted to the modified production system needs coming from the evaluation criteria for the WSV. Next, the defined work system is executed and the target achievement of the work system is monitored to maintain a target-oriented work system structure and behavior following the concept of self-organized systems.

6. Conclusion and outlook

The first approximation for a target-oriented work system design and autonomous execution of intralogistics processes for the changeable factory environment of the pilot factory Werk150 described in this paper has shown a significant potential to cope with changing production requirements of versatile production systems. One of the next steps will be covered in a second approximation which will be the further development of the described autonomous control method focusing on logistics goals towards a self-organized and autonomously controlled method covering cost and performance goals as well as the WSV of logistics and assembly/production in a joint equation system enabling target-oriented decisions with dynamic source and sink relations. Also the autonomous initiation of the work system (re-)configuration will become a system inherent feature following the approach of self-organized systems anticipating a target-oriented system (re-)structuring in an autonomous manner. Through this widening of the scope of self-organization and autonomous control to the entire production system including the logistics processes, a target-oriented system behavior might be achieved also in case of arising internal and externals turbulences in the versatile production system. The hypothesis to be proven at the end is that the extension of the scope of self-organization to production and logistics improves the overall goal achievement (costs and performance) of versatile factories.

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Biography

Jan Schuhmacher, M.Sc, MBE, is a research associate at ESB Business School and part of the research, training and consultant group of the Werk150. His major field of research is the design and optimization of changeable intralogistics systems.

Vera Hummel, Prof. Dr.-Ing. has been a professor at the ESB Business School, Reutlingen University since 2010. She is a founding member of the "International Association of learning factories IALF" and the initiator of "Werk150 – the Factory on Campus of ESB Business School" for research, education and industry training.