CARV 2009

Modelling of Autonomous Control explicitly considering Orders as a Kind of Immaterial Logistic Objects in Manufacturing Processes

B. Scholz-Reiter[1]; St. Sowade[2]; T. Hildebrandt[3]; D. Rippel[4]

Abstract: The paper extends the Autonomous Logistics Engineering Methodology (ALEM), proposed to engineer logistic systems based on the principle of autonomous logistic processes, by certain aspects of immaterial logistic objects driving and trigging the manufacturing process. A hierarchical modelling concept is used to split customer orders logically into partial orders which combine different manufacturing steps. The amendments enable mapping and integration of product structures and customer orders in manufacturing up to the detail level of a single machine and are a further step to integrate autonomous control into existing manufacturing systems.

Keywords: Production Planning and Control, Logistic Object, Order Decomposition

1 Introduction

Changeable manufacturing (ElMaraghy 2009) and autonomous control (Hülsmann & Windt 2007) are recent paradigms in manufacturing systems research. The first concept encompasses the achievement of changeability for products, processes, facilities and organisations, while the latter focuses on processes in particular. Autonomous control aims to increase the robustness of a system and to reduce the complexity of its processes due to increased flexibility and local autonomy. The Collaborative Research Centre (CRC) 637 investigates the benefits and limitations of the paradigm of autonomous control in logistic processes with a focus on production and transportation logistics.

[1-4] BIBA - Bremer Institut für Produktion und Logistik at the University of Bremen, Hochschulring 20, 28359 Bremen, Germany, Tel. +49-421-2185538, E-mail: {bsr, sow, hil, rip}@biba.uni-bremen.de

1.1 Research Question

The Autonomous Logistics Engineering Methodology, ALEM, (Scholz-Reiter, *et al.*, 2009), is developed by the CRC 637 to model a logistic systems based on the principle of autonomous control. It focuses on production logistics and the relevant physical logistic objects, e.g. half finished products and resources like machines. Benefits of autonomous processes have been shown in simulation studies for manufacturing scenarios with *n* x *m* machines (Scholz-Reiter, *et al.*, 2006a) and for routing in transportation networks (Scholz-Reiter, *et al.*, 2008a).

1.1.1 Restrictions in Present Modelling Methodology

The current reference model (Fig.3.) does not distinguish strictly between the different views of ALEM (Fig.1.). Some elements shown in the structure view can be represented in the ability view or in the knowledge view as well. Even if this is caused by the kind of application used, this fact might indicate limits of the modelling methodology caused by underlying assumptions, for example.

ALEM does not describe how immaterial logistic objects, like “orders”, shall be modelled. Many physical logistic objects are modelled in the structure view, but the “order” is the only immaterial logistic object in this view. Orders represent one specific commodity travelling autonomously through the production network. It is induced by a production planning and control (PPC) system into the job shop for execution. Neither a dispatch mechanism is defined that triggers a single process nor is a definition provided for the exact meaning and the type of an order.

1.1.2 Integration of Order Decomposition and Assembly Processes

A detailed model is required to describe immaterial objects, in particular “orders”. The first order a company receives is a customer order. Usually this order cannot be processed directly by a manufacturing system, because of its low granularity. The order’s granularity must be refined by decomposition. New meta-model elements and preconditions for modelling of orders have to be integrated into the modelling framework. The methodology should consider customer orders directly and the consequences for the modelling methodology have to be discussed.

In addition, manufacturing usually involves processes in production and assembly, but ALEM is designed to model production processes only, neglecting an essential part of the real world. The integration of assembly processes may lead to additional requirements, new elements of the notation meta-model or to changes in the procedure model. An amended model has to be able to cope with synchronisation issues at assembly stations, as well as with order decomposition and management.

1.2 Structure of the Paper

After introducing the research question in section 1, the next section explains the concept of autonomous control in logistics. It describes the modelling methodology ALEM and gives an example of the status quo reference model.

The third section introduces the proposed amendments of ALEM. It provides the concept of an order hierarchy and decomposition, as well as changes in the view concept, in the notation and in the procedure model. A new structure reference model is provided too. The last section summarises the work and gives an outlook for future research.

2 Modelling of Autonomous Control

Objectives in PPC systems can be divided into economic and logistic ones from which the latter can be subdivided into logistic costs and logistic performance. Relevant objectives are high utilisation, availability, productivity, and rate of in-time delivery as well as low inventory, process costs, and throughput times. (Scholz-Reiter, *et al.*, 2005a, Scholz-Reiter, *et al.*, 2007c, Wiendahl 2005)

The objectives are accompanied by aspects like increased flexibility, adaption of different lot sizes and product variants, as well as a reduction of lead times and an increase of on-time delivery rate (Wiendahl 2005, Luczak, *et al.*, 2001, Scholz-Reiter, et al., 2005a). Autonomous control is seen as a possibility to better achieve these objectives leading to positive emergence and increased system robustness.

2.1 Autonomous Control

Roots of the term autonomous control are located in biology and physics which tried to understand autonomy and self-organisation. Other sources of research are artificial intelligence and control theory (Scholz-Reiter, *et al.*, 2006b).

2.1.1 Definition of Autonomous Control

The CRC 637 defines autonomous control as "processes of decentralised decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity." (Windt, *et al.*, 2008).

2.1.2 Characterisation of Autonomous Control

Complex autonomous systems can be structured into three layers (Windt, *et al.*, 2008). The decision system layer includes the decision-making ability, as well as planning and control functions. The information layer contains information storing, communicating and processing abilities, e.g. sensing of the environment and its own state. The execution system layer enables logistic objects to react flexibly to dynamic changes in the environment. Based on the level model Hülsmann and Windt (2007) developed a catalogue of criteria to characterise the level of autonomous control of a system.

Preconditions for implementation of autonomous control are the existence of decision alternatives within a logistic network and the presence of decision competence at logistic objects in form of knowledge about methods and algorithms. The methods can be implemented either normative by the system designer or they can be explored by the logistic object itself with self learning strategies. The autonomous logistic objects are lead by their own local objective system given by the system designer. However, no guarantee can be given for a certain global behaviour or performance (Scholz-Reiter, *et al.*, 2007c). Decision alternatives can be generated by redundancy of types of resources, manufacturing steps, or links across product structures (Scholz-Reiter, *et al.*, 2005c).

2.2 Concept of Modelling, Views and Notation in ALEM

The conceptual approach for modelling autonomous logistic systems is based on the UML abstraction model. The notation relies on standard UML diagrams as far as possible and is extended by certain elements and diagrams, e.g. a knowledge map and a layout diagram (Scholz-Reiter, *et al.*, 2007a, OMG 2009).

System and process models usually imply a high degree of complexity. This complexity can be handled by applying a view concept to focus at specific aspects of the whole model (Scheer 2001). Figure 1 shows the view concept for modelling of autonomous logistic processes (Scholz-Reiter, *et al.*, 2005b). It consists of five views and distinguishes between static and dynamic sub-models describing structure and behaviour each. The micro view describes the elements inside model and the macro view the interaction between the elements.

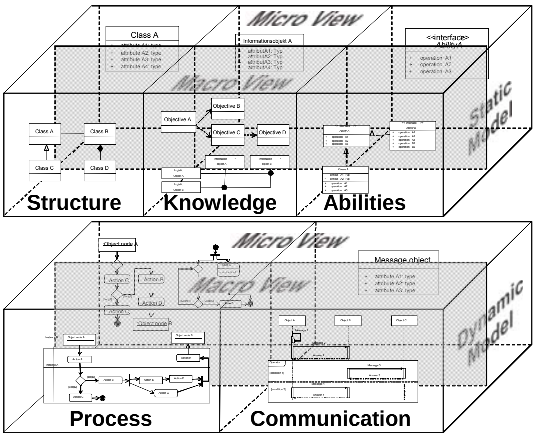

Fig. 1. ALEM View Concept (Scholz-Reiter, *et al.*, 2007b)

The *structure view* describes the relevant logistic objects in a class diagram. A layout-diagram of the shop floor supplements the abstract object classification.

The *knowledge view* denotes knowledge which has to be present at each object. It can be derived from the process view and must be specified location and form.

The *ability view* shows type and structure of abilities being required by logistic objects. Abilities can be split into sub-abilities and interpreted as abstract sets of operations. They are realised by interfaces and are associated with logistic objects.

The *process view* uses activity diagrams and state machines to focuses on the logic-temporal sequence of activities and states of production control processes.

The *communication view* describes the object's interaction and the information exchange. The messages content is modelled in class diagrams.

2.3 ALEM Procedure Model

Scholz-Reiter *et al.* (2008b) propose the procedure model ALEM-P (Procedure) to guide the user in the modelling process of an autonomous logistic system (Fig. 2.). Although the procedure's steps show a straight sequence, the modelling order differs in certain cases. If a specific algorithm for autonomous decision making shall be employed, this process must be described before modelling of the abilities. Feedback loops allow to include new aspects of the system that appear while modelling. The procedure model allows being followed top-down and bottom-up.

Objectives are a precise kind of knowledge that is allocated at each logistic object. Decisions depict the micro view of a decision method, while processes are part of the macro view. Both belong to the process model. Step one to seven refer to modelling of the system on an abstract level while the eights step is used to instantiate this model and to configure the spatial layout of the system elements.

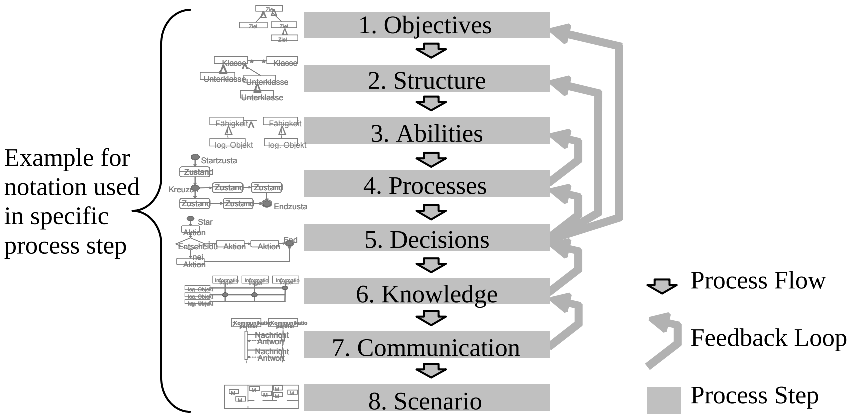

Fig. 2. ALEM Procedure Model (Scholz-Reiter, *et al.*, 2007b)

2.4 ALEM Structure Reference Model

Figure 3 depicts the ALEM structure reference model as base of an autonomous system design. The logistic object is the centre, owns a set of objectives for decision making and communicates via messages. Customer order, commodity and resource are specialised logistic objects and inherit their attributes and methods. A machine is a special type of a resource being able to execute production steps. Application of a production step changes the commodities type. Customer orders are composed of order items and are fulfilled by commodities of a certain type.

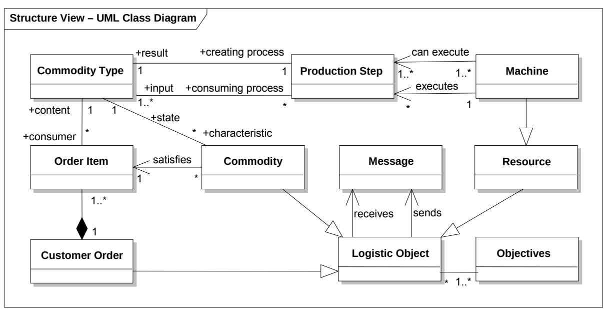

Fig. 3. ALEM Structure Reference Model (Kolditz 2009) as UML class diagram

3 Enhancing Modelling of Autonomous Control with ALEM

The ALEM meta-model will be extended to describe the concept of customer orders and object properties. This implies the introduction of the new concept and a further definition of semantic and syntactic elements within the ALEM framework.

3.1 Concept for Hierarchical Order Decomposition

A concept of commodity property management within the manufacturing process and a product structure diagram (PSD) are proposed to decompose and model orders in ALEM. Each intelligent object retains a list of properties, describing its actual state. The properties consist of a name and a value. The new diagram depicts the product structure in terms of production and assembly steps, making use of the object’s properties. Each PSD explains the complete structure of a single orderable product by defining its manufacturing steps, the objects that are necessary to perform a step and the result from application of a step. The objects properties are affected by and used in the manufacturing steps.

3.1.1 Order Decomposition and Execution

Customer orders are mapped unto a PSD (Fig.4.a.), which then is decomposed into several system internal orders (Fig.4.b.). The decomposed manufacturing orders can be classified into assembly orders and production orders.

A production order consists of a structured list of all production steps to be taken until either an assembly step, or a leaf node is reached. Assembly orders consist of one assembly step. After the decomposition, the manufacturing orders have to be communicated to instances of the objects that are going to execute them. Therefore, a kind of register is introduced. The customer orders register to it, while it is used by the commodities to acquire new manufacturing orders. If an object decides to accept one of these manufacturing orders, manufacturing goals are passed to it, which represent the respective path in the PSD. Following the example given in Figure 4.b. the “Hull”-object on the leftmost leaf node will receive the sequence of goals ProductionOrder.2, AssemblyOrder.1 and ProductionOrder.1. Logistic objects use these goals to negotiate autonomously with the respective resources about which and when to use a resource according to their objectives.

PSDs allow modelling production processes which fork and rejoin (Fig.4.). When there is more than one branch within a production order, the logistic object chooses between the next step of each branch. Either way, all production steps of each branch have to be satisfied, before the branches can rejoin.

3.1.2 Synchronisation

Assembly steps can only be performed when all required logistic objects have finished their preceding manufacturing tasks and are present at the assembly station. ALEM has to allow modelling of different concepts of synchronisation, which can be performed either decentralised by the commodities, or rather centralised by the assembly resources. The latter case is described below as reference synchronisation process.

Logistic objects looking for a particular assembly step request this step form one or several suitable assembly resources. The resource waits until all necessary logistic objects have requested this assembly. Then it collects and aggregates all of the logistic objects goal-functions and returns the result to the participants. The method assures that each participant receives the same combined rating for each resource, resulting in the same decision on which machine to join.

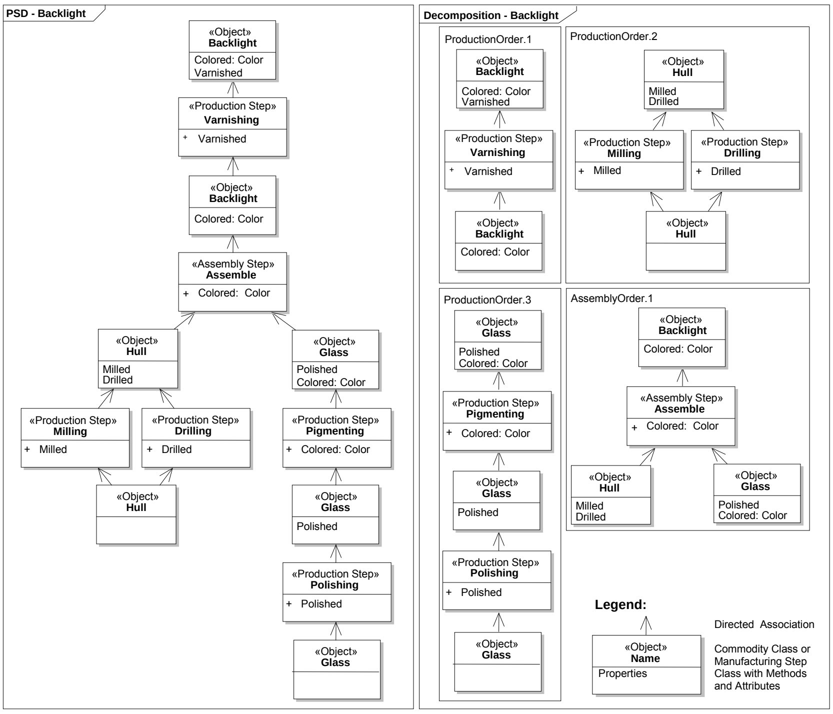

Fig. 4. Product Structure Model (a) and decomposition to manufacturing orders (b)

3.2 Amendment of View Concept, Notation and Procedure Model

Application of the concept of order decomposition to the ALEM Model requires several changes of its view concept, notation and procedure model, as well as updating and refining of the structure reference model.

3.2.1 Notation of Product Structure Diagrams

Product structure diagrams show manufacturing steps. They define which commodity types are present in a modelled process and how they interact with the manufacturing steps. A PSD is considered as a directed graph, pointing from the leaf nodes towards the root node. The root node describes the end product ("Backlight"-Node topmost in Fig.4.a.); the leaf nodes represent the commodities, from which the end product is manufactured ("Hull" and "Glass" on the bottom of Fig.4.a.). Three different kinds of nodes are used to define the product structure. Object nodes represent commodities and consist of the commodity type and a set of properties describing the objects actual state. Assembly nodes combine at least two object nodes to a new object node and add new properties (e.g. in centre of Fig.4.a.). Production nodes modify properties of an object node passing through (“Milling” or “Drilling” on Fig.4.a. left branch). Each object node, except for the root node is followed directly by one or more production nodes or by exactly one assembly node. Each manufacturing node is followed by one object node, whose properties and type reflect the changes made by the last process step.

Every object node used in a PSD retains a list of properties. These are designed to be as generic as possible. They are identified by a textual name and additionally hold a value. This allows to model properties in different granularity. It is possible to express that an object is painted, by applying the property (Property: ”painted”, Value: blank) just as well as a very precise description of single aspects like: (Property: ”hole.diameter” Value: 9mm). By default an assembly step replaces all properties from the input nodes by new ones, while a production step copies all properties. Other property modifiers may either be deleting or creating properties. Removal of properties from an object within this diagram does not imply that the information is removed from the system. Abilities can be implemented to store this information for further use. PSDs have to be integrated into the knowledge view. Knowledge maps are used to assign the modelled manufacturing steps to the logistic object that will perform them.

3.2.2 Mandatory Abilities

Mapping and decomposition of customer orders as well as accounting of goal-creation from manufacturing orders are realised as abilities. In the reference model, these abilities are associated to the order register. Synchronisation is defined in the ability, process and communication views and is assigned to the respective objects.

This setup allows the implementation of different strategies of autonomous control for different models. For example, the register’s abilities can be assigned to other, different objects to decentralise this process for large scaled scenarios.

3.2.3 Implications on the ALEM-Procedure Model

Product structures are knowledge applying to a specific manufacturing scenario. Thus modelling could take place in the sixth or eights step in ALEM-P. A specific product structure instantiate the decomposition of a specific product placed in a customer order, but it is not a generic modelling of an autonomous system. Hence, PSDs appear in the knowledge view and are modelled in the eights procedure step.

Although PSDs could be defined earlier because of their importance for order decomposition, this position is well suited. PSDs neither relay on information defined earlier, nor offer information, which is necessary to define other aspects of the model. The semantic meta-model of ALEM-P is not changed.

3.2.4 Amendments to ALEM Structure Reference Model

Customer orders are treated as intelligent objects. They are defined in the structure view class diagram and consist of assembly and production orders. Their necessary abilities and knowledge are assigned the in the respective views. A customer order includes at least the amount and type of ordered products. Other information can be extended if appropriate. The entry commodity type becomes mandatory, because it is referenced and instantiated by PSDs. An order register is represented as intelligent object. It manages order mapping, decomposition, accounting, and goal-creation (Fig.5.).

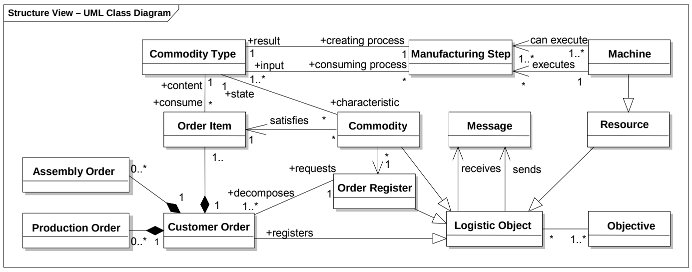

Fig.5. UML Class diagram of new ALEM structure reference model

4 Conclusions and Outlook

Integration and embedding of assembly processes enable a more precise and extensive way to model autonomous manufacturing processes. Knowledge about product structures is already present in companies and can be used with little effort. The way of knowledge representation in ALEM does neither restrict possible strategies of autonomous control nor the way in which they can be realised. The reference model can be adapted to other strategies by reusing or redefining some of its components. Next step will be the embedding of the ideas in ALEM-T (tool).

Different implementations and allocations of the introduced processes, e.g. synchronisation or order decomposition, will be examined with ALEM to test the modelling capabilities of the meta-model and the reference model.

Further research has to be carried out to model an extended manufacturing reference scenario. A simulation component has to be integrated in ALEM to find out how the autonomous processes work and how the system performs under certain conditions, like hop-wise decision algorithms. Simulation is a precondition for evaluation of different system architectures and infrastructure configurations.

Acknowledgement

This research is funded by the German Research Foundation (DFG) as part of the Collaborative Research Centre 637 “Autonomous Cooperation Logistic Processes – A Paradigm Shift and its Limitations” (CRC637).

5 References

ElMaraghy HA (2009) Changeable and Reconfigurable Manufacturing Systems, Springer, London

Hülsmann M, Windt K (eds.) (2007) Understanding of Autonomous Cooperation and Control in Logistics – The Impact of Autonomy on Management, Information, Communication and Material Flow. Springer, Berlin

Kolditz J (2009) Ein Vorgehensmodell zur Modellierung selbststeuernder logistischer Prozesse. PhD-thesis, Universität Bremen

Luczak H, Eversheim W (eds.) (2001) Produktionsplaung und -steuerung: Grundlagen, Gestaltung, Konzepte, 2. edn. Springer, Berlin Heidelberg New York

OMG Group (2009) UML-Specification 2.2. URL: http://www.omg.org/technology/documents/formal/uml.htm, last access: March 5th 2009

Scheer AW (2001) ARIS - Modellierungsmethoden, Metamodelle, Anwendungen, 4. edn. Springer, Berlin Heidelberg New York

Scholz-Reiter B, Windt K, Kolditz J, Böse F, Hildebrandt T, Philipp T, Höhns H (2005a) New Concepts of Modelling and Evaluating Autonomous Logistic Processes. In: Proceedings of 2004 IFAC Conference on Manufacturing, Modelling, Management and Control. Athens, Greece

Scholz-Reiter B, Kolditz J, Hildebrandt T, Höhns H (2005b) Modelling Smart Label-Supported Production Processes. In: Soliman KS (ed.) Internet and Information Technology in Modern Organizations: Challenges & Answers, IBIMA- International Business Information Management Association. Kairo, Egypt, pp. 408-413

Scholz-Reiter B, Höhns H, Kolditz J, Hildebrandt T (2005c) Autonomous Supply Net Coordination. In: Proceedings of 38th CIRP Manufacturing Systems Seminar. Florianopolis, Brazil, CD-ROM 7 pages

Scholz-Reiter B, Philipp T, De Beer C, Windt K, Freitag M (2006a) Einfluss der strukturellen Komplexität auf den Einsatz von selbststeuernden logistischen Prozessen. In: Pfohl HC, Wimmer T (eds.) Steuerung von Logistiksystemen - auf dem Weg zur Selbststeuerung. - Konferenzband zum 3. BVL-Wissenschaftssymposium Logistik, Deutscher Verkehrs-Verlag, Hamburg, pp. 11-25

Scholz-Reiter B, Höhns H (2006b) Selbststeuerung logistischer Prozesse mit Agentensystemen. In: Schuh G (ed.), Produktionsplanung und -steuerung. Grundlagen, Gestaltung und Konzepte. Springer, Berlin Heidelberg New York, pp. 745-780

Scholz-Reiter B, Kolditz J, Hildebrandt T (2007a) UML as a Basis to Model Autonomous Production Systems. In: Cunha PF, Maropoulos P (eds.) Proceedings of the 3rd CIRP Sponsored on Digital Enterprise Technology. Setúbal, Portugal

Scholz-Reiter B, Kolditz J, Hildebrandt T (2007b) The Autonomous Logistics Engineering Methodology (ALEM). In: Maropoulos PG, Newman ST (eds.) Proceedings of 4th International CIRP-Sponsored Conference on Digital Enterprise Technology (DET2007). Bath, UK

Scholz-Reiter B, Freitag M (2007c) Autonomous Processes in Assembly Systems. CIRP Annals 56, pp.712-729 (2)

Scholz-Reiter B, Rekersbrink H, Wenning BL, Makuschewitz T (2008a) A Survey of Autonomous Control Algorithms by Means of Adapted Vehicle Routing Problems. In: Proceedings of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis, Haifa, Israel, 07. - 09. July 2008.

Scholz-Reiter B, Hildebrandt T, Kolditz J (2008b) Modellierung selbststeuernder produktionslogistischer Prozesse – die Modellierungsmethode ALEM. In: Mattfeld DC, Günther HO, Suhl L, Voß St (eds.) Informations- und Kommunikationssysteme in SCM, Logistik und Transport. Teilkonferenz der Multikonferenz Wirtschaftsinformatik 2008. Paderborn, pp. 173-185

Scholz-Reiter B, Kolditz J, Hildebrandt T, (2009) Engineering autonomously controlled logistic systems. International Journal of Production Research 47:1449-1468 (6)

Wiendahl HP (2005) Betriebsorganisation für Ingenieure. Carl Hanser, München

Windt K, Böse F, Philipp T (2008) Autonomy in production logistics: Identification, characterisation and application. International Journal of Robotics and CIM 24:572-578 (2)