A Contribution to the Application of Autonomous Control in Manufacturing

B. Scholz-Reiter, St. Sowade, D. Rippel, M. Teucke, M. Özsahin and T. Hildebrandt

***Abstract*—**The apparel industry is a prime example for the field of manual manufacture. Problems in manufacturing control are caused by manual handling of garments and influence the availability and correctness of information. This bad information quality leads to problems along the supply chain from production to disposition. Automated data management based on radio frequency identification technology is proposed to solve these problems. Autonomous control can be established on top to increase the system robustness and flexibility and to enable smaller manufacturing batch sizes. Although autonomous control is easily applicable in highly automated systems its application in manual processes is generally difficult. Three different system architectures are discussed, diverse technical approaches are analyzed and decision is made for one approach based on radio frequency identification and manufacturing batches that suits the apparel scenario well.

***Keywords*—**autonomous control, apparel industry, production planning and control, smart labels, system architecture.

I. Introduction

GOODS , services, information and other immaterial goods are manufactured in processes of creation, manufacture, assembly and transport. Each process requires a set of input factors that will be transformed into the desired output factors. Typical categories of input factors are raw materials, equipment and human work [1].

The transformation processes are executed either by human workers manually, or in automation by machines. A manufacture scenario is considered to be manual if the majority of the process steps are performed by human workers. Typical examples are the assembly of special purpose machines or railway vehicles, as well as manufacture in the apparel industry [2]. This article uses the latter case as example due to its very high degree of manual work and corresponding low degree of automation [3].

The textile process chain includes manufacture of fibers by the fiber industry, forming, dressing and colorizing of fabric by the textile industry, manufacture of ready-to-wear garments by the apparel industry and distribution to consumers by garment retailers (Fig. 1) [3], [4]. Up to 80% of the apparel manufacture processes are performed manually. Labor costs determine the total manufacture costs [3]. For these reasons, garment manufacture has been shifted to a large degree to low labor cost countries located e.g. in Eastern Asia [4], [5]. European garment suppliers have adapted their role towards planning and coordinating activities. Their logistics bridges large geographical and cultural distances and leads to problems, like long lead times as well as misunderstandings between manufacturer and distributor [3], [6].

Fig. 1 Elements of the Textile Process Chain [4]

In addition, market demand is highly volatile and products exist in many different variants. Seasonal order cycles with fixed dates for ordering, production and delivery are supplemented by contracts that grant large retailers strong influence in development of garment assortments [7]. In never-out-of-stock delivery (NOS) suppliers are responsible for continuous replenishment of retailer stocks within a few days or less than a day from local distribution centers, where sufficient stocks have to be kept to guarantee full service levels for specified volumes. Hence delivery volumes are rigidly coupled to actual end customer demand [6].

Conventional approaches for production planning and control (PPC) do not fit properly here [8], [9]. They suffer from unrealistic premises like predictable throughput times, absence of production bottlenecks, fix operation times per order and short machinery downtimes [10]. They owe coupling of PPC processes and tasks and are not able to map the high complexity of real production systems to a globally consistent model. A dominant central planning top-down approach prevents local problem solutions. Central planning

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processes do not consider company specific properties, lead to inflexibility and cannot react in real-time to changes in the production system until a new global planning run is made [11].

A. Research Question

The apparel industry is situated in the center of the textile process chain. Most of the production and assembly steps are performed manually. Execution of simple tasks is marred by errors, e.g. miscounting the number of garment articles that have been put into a trolley or into a package at the manufacturing site. The faulty information is transmitted to the customer later, who on his part, is unable to calculate the correct number of garments being in manufacture and in transport. Large batch sizes and high lead times add further uncertainness to the textile process chain.

The article aims to identify system architectures for the application of autonomous control in manufacturing scenarios characterized by manual work. System elements, processes and structures shall be identified that are capable to provide consistent information, achieve smaller batch sizes, increase the robustness against process errors and lead to more flexible manufacturing processes in the apparel industry. Automated identification and communication technology and autonomous processes are potential solutions. Their capabilities shall be analyzed in the context of the application area.

The manufacturing processes of the apparel industry will be investigated exemplary from a case study of a German jeans supplier. Possible solutions shall be provided for the general problems mentioned in the previous section. Aspects of the supply chain shall be mentioned only, if they are originated in manufacture. But they are not in the main scope here.

B. Paper Outline

The first section introduced the general situation of the apparel industry, pointed out the research question and outlined the paper’s structure. The second section depicts existing solutions for selected problems. The concept of autonomous control is introduced in the third section. It is considered as a new method to cope with the problems noted beforehand. The section defines autonomous control in manufacturing and describes different system architectures of autonomous control in detail. The modeling framework, autonomous logistics engineering methodology, ALEM, is introduced as well. It follows a system development cycle model, contains a view concept for handling the systems complexity and a procedure model and is supported by a software tool. Furthermore, a couple of simulation studies are quoted to show the impact of autonomous control in manufacturing scenarios.

Section four provides a case study of a German apparel company. It describes the manufacturing scenario by its layout and processes. Current problems are pointed out as well.

Section five presents three different scenarios for application of autonomous control and relates them to the system architectures noted in section three. Finally, a fourth scenario is composed taking into account the positive and negative aspects of the other scenarios. Certain important system elements will be described in more detail.

The paper gives conclusions of the research work, highlights the most important aspects for better understanding and provides remarks for implementation of autonomous control in manual driven manufacturing scenarios. The section closes with an outlook to future research.

II. Existing Solutions

Different solutions have been proposed to cope with the problems mentioned in business models, transport logistics and production logistics. They can be grouped into organizational, technological and control strategy approaches (Fig. 2). This article focuses on technical and organizational solutions with emphasis on auto identification technologies. A discussion of different control strategies can be found in [12].

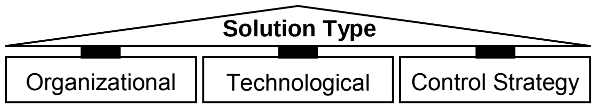

Fig. 2 Types of Existing Solutions

Organizational solutions seek to improve production and supply chain management to achieve quick and efficient consumer response. Vertical integration is one strategy. In this case, a company accumulates different functions along the value added chain. Either a retailer takes over the replenishment logistics, or a garment supplier establishes own retail and sales points. A trend towards vertical integration along supply chains can be observed, either by implementation of shop-in-shop concepts or by opening of outlets and networks of retail shops. Prominent examples can be found in the literature [13], [14], [15] and [16]. A second organizational strategy emphasizes collaboration between independent market players who retain their roles along in the value added chain but agree to collaborate in joint planning and coordinating their future operations. Cooperation includes share of information on current and future sales, demand, supply and stocks, via electronic data interchange channels. These concepts are known as collaborative planning, forecasting and replenishment or CPFR [17].

Recent progress in information and communication technologies (ICT) offers potentials to solve process control problems by improved data management. Auto-identification via radiofrequency (RFID) is the most notable technology here. Transponder devices carry an antenna and a microchip for wireless identification purposes. The use of RFID technology can improve the quality of data acquisition, storage, processing and distribution in all logistic processes at every unit level whereas costs for data processing are low. The transponder tag is able to store complex product specific information, like history records of the manufacturing process as well as a simple unique identification number. The tag can be accessed even if there is no line-of-sight to the reading or writing device. It can be mounted on every physical logistic object, such as single components, finished products, packages, or bigger batches [18], [19], [20]. Additional technologies can be used to enhance the transponder tag for real-time, dynamic, sensing and mobility purposes [21], [22] and [23].

III. Application of Autonomous Control

The problems can be addressed in a two stepped process. First the degree of automation can be increased to overcome information problems in the manufacturing processes. RFID seems to be appropriate here. Once the technology is introduced, autonomous control can be established on top to increase the workplaces utilization rate, system robustness and to enable smaller batch sizes. Principles and design methods of autonomous control will be introduced in this section. The application of RFID in an apparel scenario is described later on in section five.

A. Definition

Roots of the term autonomous control are located in physics and biology. Both investigate the principle of autonomy and self-organization. Later on, informatics applied the concepts to artificial intelligence and engineering science adopted the concept in the subject area of control theory [24].

The collaborative research center 637 analyzes autonomous control in logistics since 2004 and defines it as: “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 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” [25].

The definition describes the maximum level of autonomous control a system can have. However, specific applications can have a lower level [25]. In accordance to systems theory autonomous control implies that abilities are transferred from the total system to its elements [26]. As a consequence logistic system elements have the ability “to process information, to render and to execute decisions on their own” [25].

An important precondition is the presence of decision points within the manufacturing and supply network. The value added chain can be modeled as network of decision points, which allow logistic objects, like orders, resources, or goods, to move through and to act within the network. The autonomous logistic objects are guided by their own local objective system designed by the system designer. Alternatives and decision points of a network can be generated, for instance, by redundancy of types of certain resources and production steps, or by redundancies within the product structure [27].

B. Architectures

Potential implementations of autonomous control differ in their degree of autonomy and centralization. They range from completely external control to absolute autonomous control [25]. Fig. 3 contrasts classical PPC-systems, noticed as current systems, to different autonomous architectures.

The decision for a specific architecture is based upon several criteria. They refer either to the fulfillment of preconditions by the current technical system, like present elements, hardware, machines, workplaces and their organization, or to their available abilities. Further, criteria with impact in management and social issues are important too. Effects at the production site, the supply chain and to stakeholders, workers and consumers for instance, need to be mentioned here. Costs and benefits have to be compared for each alternative. The different types of architectures are described below.

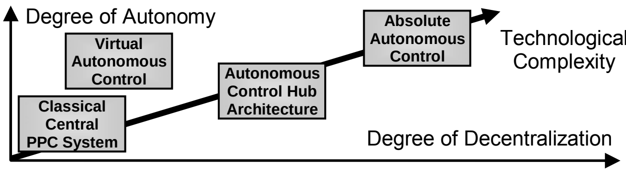

Fig. 3 Architectures of Manufacturing Control

In the *absolute autonomous control architecture*, each object within the system is an autonomous logistic object. It is able to render and execute decisions of its own. There exist two different types of system elements that can be employed as autonomous logistic object in a manufacturing scenario. On the one hand, there are commodities like finished or half-finished goods, parts, components, raw materials, additives and operating materials. On the other hand, there are resources providing a certain service to commodities, e.g. machines or production centers. Human workers and their workplaces also provide a service to commodities and are put in the same class for this reason. In terms of apparel manufacturing, each sewing machine, workplace and garment component follows its own objectives and has to be equipped with the respective abilities.

The absolute autonomous control architecture is characterized by the highest technological complexity from all system architectures noticed in Fig. 3. Also, it is expensive to equip each logistic object with certain abilities, e.g. by attaching transceivers and small computers. The impact on current processes is high. Commodities, machines and workplaces will probably communicate continously to gather required information, due to the high degree of decentralization. Definition and evaluation of local objectives and decision strategies will be complex. Management of the system as a whole is supposed to be difficult. In particular, the architecture fits scenarios marked by a high degree of automation where the abilities of the present logistic objects can be used for purposes of autonomous control.

The *hub architecture* is located between the absolute and the virtual autonomous control architectures. Its degree of autonomy is lower than in both alternatives, but the degree of decentralization lies in-between. A hub is a system element that follows its own objectives and decision methods and provides these abilities as service to other logistic objects, too. In this understanding, the hub architecture establishes a kind of master-slave relation between certain logistic objects. Thus, the abilities of decision making and execution are not equally distributed between logistic objects. Two design concepts can be distinguished. First of all, machines and transport devices can be noticed as hubs in a resource centric hub architecture. The resources will execute the tasks that are required by autonomous control. The resource centric hub architecture is preferable if it is impossible to provide all necessary functionality to commodities, e.g. if the hardware is too large to be applied or if a commodities functionality is too low. Secondly, commodities act as hubs if they offer certain abilities to other logistic objects. A commodity centric approach can be well suited, if normally several commodities share equal characteristics in type, order, date of delivery or batch size. In such a case only a few of them need to be equipped with the required abilities to render and execute decisions for all of them.

The hub architecture offers several advantages to reduce the number of required smart tags. First of all, in a manufacturing scenario in which computer numerically controlled (CNC) machines are present, these machines already contain computers, as well as common computer and network interfaces. Both can be used for decision rendering and communication with other logistic objects. Secondly, commodities do not have to be equipped with the ability to render decisions on their own. They must only be able to store and transmit their objectives and the desired decision method to a hub and they must be able to receive, store and execute the result from a hub. Even if CNC-machines are not available in apparel manufacture in general, the hub architecture offers the advantages of autonomous control whereas the effort for high developed smart tags is low. Hubs can be implemented at each work station to control the manufacturing process of the garments. The systems complexity is lower than in absolute autonomous control scenario.

A hub architecture can be interpreted in the context of the service oriented architecture. Operations which are performed by some of the intelligent logistic objects are offered as services to other objects. This allows an effective reuse of present abilities while default communication channel can be used to offer and request services in a closed system [29].

Virtual autonomous control is the third system architecture for employing autonomous control in manufacturing. The ability to render decisions is delegated to a central, real-time operating computer system. Each logistic object is represented in this system by an autonomous agent that follows its own objectives and employs its own decision methods. The resulting decisions of each agent are messaged to the respective logistic objects for execution. Decisions are made autonomously within a central system, but are executed in a decentralized manner. This system architecture does not differ strongly from current PPC systems. For this reason implementation of virtual autonomous control is assumed to be much easier than in the two cases described previously. Nevertheless, each real logistic object has to be equipped with decision execution, transceiver and storage capabilities. The control systems complexity will be as high as in total autonomous control, because objectives and decision strategies must be defined for each agent. Tracking of the systems state is supposed to be easier than in total autonomous control due to the higher degree of centralization. The execution system offers the same advantages as in absolute autonomous control, but it is highly dependent on the central control computer.

C. Autonomous System Development Cycle

Development of autonomous logistic systems requires specification of the system, its simulation and software programming, configuration of the infrastructure that is required for autonomous control in particular, as well as an economical evaluation by a cost and benefit analysis [30]. These steps can be performed in a cyclic manner to improve the system design iteratively (Fig. 4). An iterative approach is used, because the development of systems and processes is a complex task, which includes specification, validation and refinement [31].

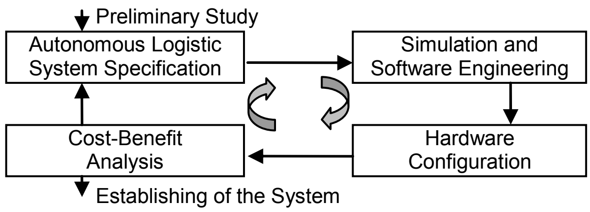

Fig. 4 Autonomous Logistic Development Cycle [28]

A preliminary study forms the basis to analyze the existing system and to design explicit goals anticipated to be reached on the implementation of autonomous control. Based on this study, recommendations for a specific architecture and ideas for the configuration of the system as for concrete decision methods can be derived. The autonomous logistic system has to be specified using the ALEM framework which is described later in this in section and results in a detailed specification of the system. This specification has to be tested and implemented during the simulation phase to validate the selection of a specific set of system parameters. Some previous simulation results for specific manufacturing systems and decision methods will be stated later. The hardware configuration is based on both preceding phases and has to be supported by the modeling tool, as well. The evaluation phase of the development cycle is part of future work.

1) The ALEM Modeling Framework

The modeling framework ALEM, Autonomous Logistics Engineering Methodology, has been developed to specify autonomous logistic systems [32]. The structure of the framework is displayed in Fig. 5.

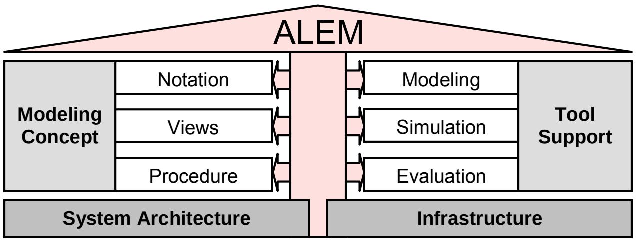

Fig. 5 ALEM Modeling Framework

The decision for a specific system architecture and infrastructure, current and planned, is the base for developing an autonomous controlled logistic system with ALEM. The framework provides a modeling concept which includes a notation to describe the system and its elements, a view concept to focus on certain aspects while modeling and a procedure model as guide through the modeling process. Tool support shall be granted for the modeling of the system, its simulation and evaluation.

2) ALEM Notation and View Concept

The notation for modeling autonomous logistic systems is based on the unified modeling language (UML) and is extended by certain elements and diagrams, e.g. knowledge maps and a layout diagram [33], [34].

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 [35]. ALEM mainly uses five functional views to overview the complex model at a glance (Fig. 6).

Further distinction is made between static and dynamic sub-models describing structure and behavior each. The micro view focuses at the elements inside the model and the macro view describes the interaction between the elements. These supplementary views provide non-functional views at the system [12].

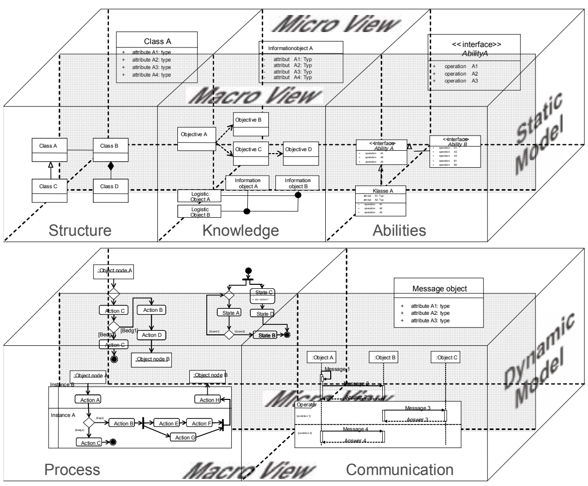

Fig. 6 ALEM View Concept [12]

The structure view shows the relevant logistic objects and their relations in an UML class diagram, as well as the spatial configuration in a layout diagram. The knowledge view structures the knowledge, which has to be present at the logistic objects to enable decentralized decision making, by use of knowledge maps and class diagrams. The ability view describes type and structure of abilities that are required by an autonomous logistic object. They can be broken down into sub-abilities and can be interpreted as an abstract set of operations. Abilities are modeled as UML-interface-classes. The process view focuses on the logic-temporal sequence of activities and states to describe the flow of material, the progress of processes and the respective control. UML activity diagrams and state machines are employed here. The communication view describes interaction and information exchange between logistic objects in UML sequence diagrams. The message content is modeled as class diagram. The communication processes are designed for a specific decision method.

3) ALEM Procedure Model

Scholz-Reiter et al. propose ALEM-P (procedure) for guidance to model autonomous logistic systems [12]. The procedure comprises eight steps (Fig. 7). The process flow arrows show the main transitions between the steps. The system designer is not bound to follow the proposed procedure strictly in straight sequence. For instance, processes have to be described before modeling the abilities of logistic objects, if a specific method for autonomous decision making shall be employed. In this case step 4 will precede step 3. Feedback loops are allowed within the modeling process to include new aspects of the system when they appear while modeling. 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, whereas processes are part of the macro view. Both belong to the process model. Step one to seven refer to modeling of the system on an abstract level whereas the eights step is used to instantiate this model and to configure the spatial layout of the system elements.

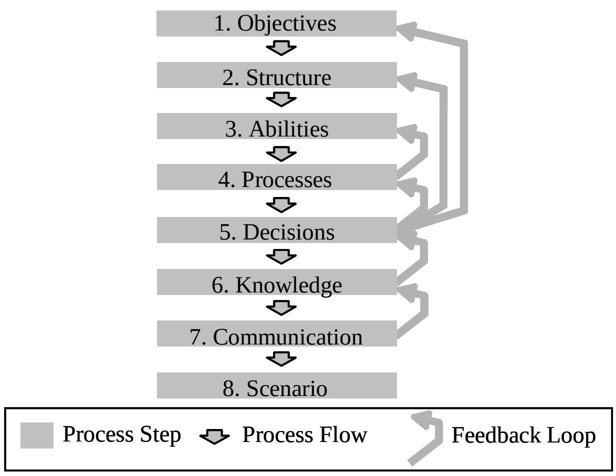

Fig. 7 ALEM Procedure Model [12]

4) ALEM Tool Support

A tool for modeling autonomous logistic systems has been proposed by Scholz-Reiter et al. [36]. It is implemented in the open source Rich Client Platform toolset using the Eclipse Modeling Framework [37], [38] and the Graphical Modeling Framework [39]. A code generator creates an Eclipse-plug-in of the specified model parts.

Fig. 8 shows a screenshot of the tool with highlighting of the most important surface elements. The model explorer shows the different models being under development. An overview of each model is provided in a hierarchical tree for all used views and diagram types. A graphical editor is located to the right. Models can be drawn at the drawing surface by use of the elements of the drawing palette. The elements are limited to relevant modeling aspects by selection of a certain view and diagram type. The diagram interconnection window is positioned to the right of the drawing palette. It allows to create and connect the current element with other views. The properties of the current diagram and detailed information about the currently selected diagram elements are displayed at the bottom of the graphic editor. To the right, but not shown in this screenshot, the user finds support for usage of the tool in form of tutorials and a description of the procedure model. The user is able to activate certain elements right out of the user support area.

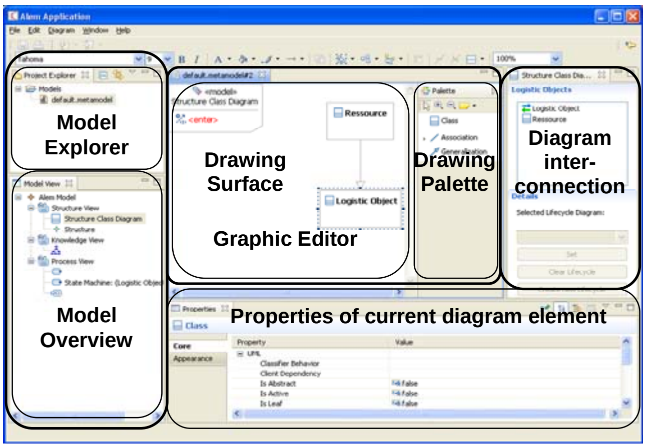

Fig. 8 ALEM Tool Screenshot

5) Simulation of Autonomous Control

Simulation studies have shown that autonomous control generally works well in manufacturing scenarios even in case of disturbances, like machine break downs. The system can react in a flexible way and can reschedule the commodities waiting in buffers.

The simulated manufacturing scenario consists of 9 machines with one input buffer each (Fig. 9). Three machines in a row offer the same service, e.g. cutting. An order accesses the system on the left side. It proceeds to one machine of the next row, if the preceding manufacturing step has been completed. At the end, the finished garment part is removed from the system. Different autonomous decision methods have been analyzed recently [12]. Decision methods can be grouped into forecast methods and past value methods.

A standard decision method is queue length estimation (QLE). The autonomous commodity, e.g. a part, forecasts the expected operation lead time to be served at a machine and selects itself the machine associated with the shortest time.

In a pheromone based approach, information on queuing and processing times of past commodities are collected and recorded for each machine and provide the decision base. Subsequent parts select the machines that have achieved the lowest past cycle time.

Both methods can be employed in the scenario, but QLE reacts faster and more flexibly than the pheromone concept. The latter method needs some time to adapt to the new situation. It performs better in situations of low dynamics but high variance in processing times [40], [41]. Although further research has to adapt these methods to the specifics of the apparel industry, application of autonomous control in apparel manufacturing processes can be recommended due to similarities in shop floor operations.

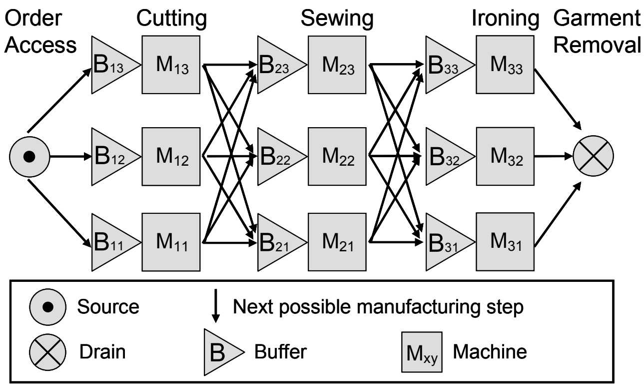

Fig. 9 Matrix Manufacturing Model [12]

D. ALEM Structure Reference Model

Autonomous systems consist of several logistic objects guided by own objectives and communicating with each other via messages. Each object has to be defined by several criteria:

- Its degree of physical mobility
- Its ability of self awareness and self-monitoring
- Its identification method towards other system elements
- Its type of flexibility in terms of timely adoption and reaction to changes in the environment
- The place and method of data storage and processing
- The type of the relevant data and the place for decision making
- How, with whom and what content is exchanged with other objects.

Fig. 10 shows the ALEM Structure Reference Model for the objects and their relations in a UML class diagram. Orders, single parts, manufacturing batches of parts or complete products, transport units, storage devices and machine tools or manual work stations are typical logistic objects in a manufacturing scenario.

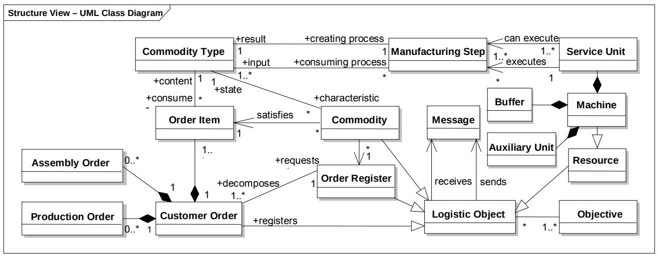

Fig. 10 ALEM Structure Reference Model

Orders are non-physical logistic objects. They are generally kept in the PPC System and released into the manufacturing site for execution. An order register is used to keep track of the released orders. A customer order can be split into assembly orders and production orders. Customer orders may initiate several manufacturing batches in the manufacturing process and result in different products. They can be attached to physical objects and share their physical mobility. As an example orders can be assigned to a certain half-finished part. They use the abilities of the hosting object, to follow their own objectives.

Resources use production data acquisition (PDA) for self monitoring and are assumed to be powered on in general. They monitor their environment ongoing and can use any point in time for decision making and communication. However, decision execution may take place only at certain points in time when other logistic objects are affected.

Machines are physical resources and are assumed to offer transformation or assembly functionality at a fixed location. Contrary, transport units are mobile physical resources which move objects at the shop floor. They can be used to take care of manufacturing batches. In this case the transport device adopts the role of the manufacturing batch as well as its abilities and duties. The service is provided by a service unit to order items and commodities, e.g. transport, storage, or processing. A service is executed in a manufacturing step to transform the commodity type as described in the specific order. Auxiliary units support the service units with computation and communication abilities for instance. Machines usually employ buffers which are located either right before the machine or the buffer is part of the service itself, as in transport units.

Auxiliary machines can be employed to provide certain service if required, e.g. wireless power supply or forwarding of communication. They have only limited capabilities, do not work necessarily as intelligent objects and are modeled as machines with auxiliary service only.

IV. Industries Driven by Manual Work: A Case Study of Apparel Manufacturing

Impacts of the problems in apparel manufacturing can be demonstrated exemplarily for a German apparel supplier, specializing in denim garments. The garment supplier operates several distribution centers being situated across Europe. Each of them satisfies local demand by supplying retailers in NOS policy. The supplier runs a garment manufacturing plant situated in China in the Perl River region to replenish the distribution centers. The plant is supplied by local raw material suppliers and coordinated via a procurement agency situated at Hong Kong. Transport of finished garments is executed by a large logistic service provider either by sea or, in urgent cases by air. The geographic locations and transport routes are illustrated in Fig. 11.

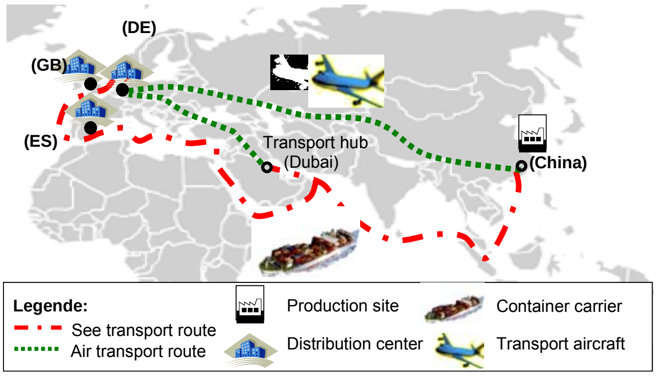

Fig. 11 Transport Network of the Case Study

The garment supply process includes the process steps production planning, procurement of raw materials, manufacturing, transport to the distribution centre, intake and storage as well as picking and shipping at the distribution centre and transport to the retailer.

A. Manufacturing Scenario

The denim garments manufacturing process can be divided into three stages. The manufacturing of unfinished garments

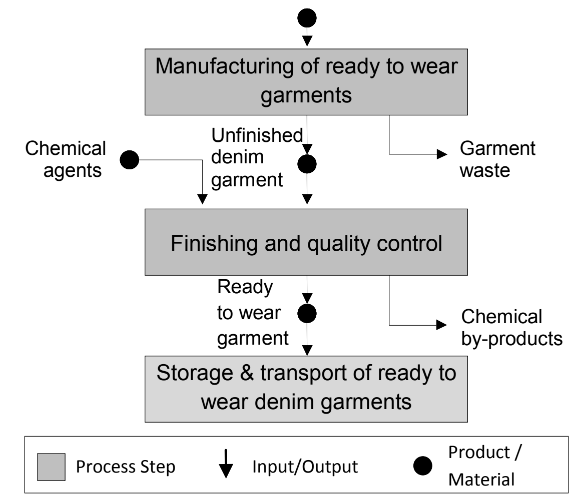

Fig. 12 Phase model of three stage denim manufacturing process (adapted from [41])

takes place in the first step, finishing and quality control is part of the second step, whereas storage and transport of ready-to-wear denim garments is located in the third step (Fig. 12).

Manufacturing of the garments includes cutting of the fabrics, embroidery (printing) and sewing. Band knifes, manual straight cutters and auto spreading machines are used for cutting. Over lock machines, single and double needles and eyelet machines are used for sewing. The exact sequence of the manufacturing steps depends on the product structure of the garments which can be characterized by type and number of fabric parts and special surface processing requirements. Finishing includes washing, thread trimming, buttoning, ironing and labeling. Quality control between the steps includes first checking, size measurement and final checking.

Fig. 13 Case Study's Factory Layout

Most work stations at the shop floor are arranged according to the job shop principle (Fig. 13). The machines are grouped at the ground floor in two sewing areas, a hall for bulk stock storage and a washing area. Manufacturing of salesman samples, finishing, labeling, packing, stone washing and cutting takes place in the upper floor. Sewing areas are organized in manufacturing lines which contain several sewing machines each. Redundancy of work stations requires allocation of batches to certain stations. The material flow through the manufacture and finishing processes as well as the execution of the manufacturing steps is carried out in sequential order. Half-finished garments, zippers, knobs and other materials are transported manually between workplaces using simple trolleys. Between and after the manufacturing steps, quality gates have to be passed, wherein the trousers are controlled manually.

B. *Current Problems*

The problems faced by this supplier are in particular:

1) Control of the manufacturing process is difficult, because there is information available which could be used for these purposes. Information about the state of orders currently in production is required.
2) On the one hand Customer order volumes are reduced while the number of demanded variants increases. On the other hand there are manufacturing batch sizes of several hundred pieces and manufacturing times of more than three months. More flexible and efficient manufacturing processes are required.
3) There are differences between the exact number of articles ordered by and delivered to the customers. Major differences are to be recognized in the distribution of product variants. This Knowledge is required about garments in transport.
4) Accounting and book keeping of stock levels for the various products and product variants is erroneous. Unexpected differences between accounted and real stocks cause sudden stock level run-outs, decreasing delivery service levels.

V. Application of Autonomous Control in the Apparel Industry

Technologies and processes are the main enablers for employment of autonomous control and provide certain capabilities to a logistic object. They can be derived directly and indirectly from the definition of autonomous control (Fig. 14). The objects require communication and identification technology, as well as self state awareness. Further, they have to be embedded in processes which provide decision points and allow decision making and execution by the object itself. Each capability can be realized in different ways in the apparel scenario.

Self state awareness deals with information about the object itself, like positioning data, the degree of fulfillment of its objectives, or data form sensors. Selection of the identification system is crucial, because reliable identification of logistic

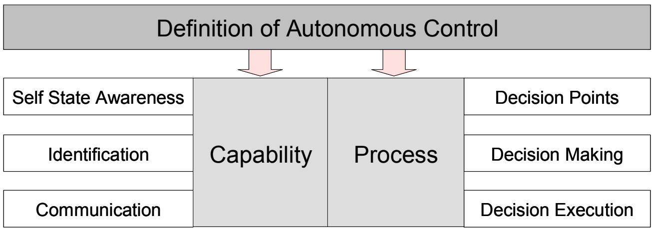

Fig. 14 Enablers for Autonomous Control

objects enables autonomous processes in manufacturing and is able to solve the information deficit of the downstream supply chain as well [28]. Thus, diverse ideas will be discussed for implementation of automated identification technology in apparel manufacturing. Identification can be provided in different stages in the manufacturing process, but the required efforts will vary as well as the availability of certain smart tags might be insufficient. Collected information needs to be transmitted to other object for further evaluation.

A. System Elements Description

System elements of the apparel scenario need to be designed form the evaluation of the case study's scenario (Fig. 13) and the ALEM structure reference model (Fig. 10). Their characteristics and relations will be explained based upon their importance.

Logistic objects in terms of apparel manufacturing can be grouped into the object types order, commodity and machine. The customer order is an immaterial logistic object. It is passed by the German garment supplier to a customer relationship management system (CRM) in the factory. Each ordered unit of garment is noticed as an order item. Orders are sub-divided into several production and assembly orders depending on the product structure of the ordered garment. Production steps usually contain cutting, washing and thread trimming. Assembly steps include sewing of different parts together, as well as connecting zippers, knobs, rivets, labels and other non fabric parts to garment pieces. Commodities are physical logistic objects and comprise raw materials, like bulk fabric and small parts, half-finished garment parts, batches of parts and ready-to-wear jeans. Commodities are routed between the processing stations of the factory. Physical logistic objects like production lines and work stations are treated as fixed positioned machines offering assembly or production services. Transportation units like trolleys are noticed as mobile machines that move commodities and orders respectively, from one workplace to another. Trolleys provide transformation of location and time to commodities which is called transportation service. A certain service can be provided by different machines like described in Fig. 9.

Physical objects are enhanced by smart tags for purposes of identification, self state monitoring, decision making and communication. The tags store general information, like the objectives of the part, provide auto-identification, process the decision method and record the processing history. Auto-identification can be realized optically by barcodes or electronically by RFID which is proposed here [18]. The tags keep object specific information, like garment's product structure, type, size and color, or processing abilities, too. Tagged parts communicate with trolleys and processing stations, to request their services in type and timely manner. They negotiate time slots for resource usage or gathering information for decision making. The tags abilities can be used each time the smart tag is powered. This certain point in time becomes a decision point for the logistic object, e.g. a garment piece.

Smart boxes are a further enhancement to smart tags. They provide a wide range of additional functions, e.g. long range communication interfaces via wireless local area network, real time online position tracking. Furthermore they provide easy to use input devices and a display for a graphical user interface and for signaling processing and state information. They are equipped with a buffer battery as electric power supply and a recharge mechanism. Recharge takes place each time the smart box is parked close to a wireless electricity transmission system (WE). WE systems are under development and are assumed to be available in future [43]. Smart boxes are expected to be much bigger than smart tags and can be mounted at machines, production lines and trolleys only.

B. Intelligent Fiber Scenario

Firstly, smart tags can be included in high density into fabric fibers during fiber or fabric production (Fig. 15). Each tag is capable to store required information, to compute decisions and to communicate with other tagged parts. The density of the tags has to be high enough to ensure that each cut out part is tagged at least once. The part is identifiable from the point it has been programmed with a unique ID. Programming takes place right after the part has been cut out of the fabric by passing an RFID gate that is positioned next to the cutting station. The RFID gate is equipped with a communication interface to obtain required data from other system elements, e.g. an order management system. Alternatively, the RFID gate can be integrated in a trolley. In this case, the tags are programmed when the fresh cut parts are put inside. Machines are able to read the tag and to add further object or process related information. Each machine or workplace is identifiable as well. It can monitor its state as idle, busy or error. The intelligent parts select a machine depending on their stored goals and the state information of the machines.

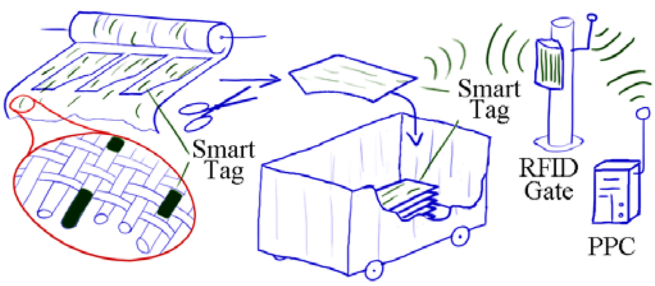

Fig. 15 Autonomous PPC – Intelligent Fiber

This procedure improves the control of the production process and the quality of information during transport, disposition and sales of the garments. It provides continuous information from the beginning of the life cycle of a part until the ready garment is sold at the end of the supply chain process. The tags capabilities can be even used for after sales services. Machines and parts act as autonomous logistic objects. The scenario is a specificity of the architecture of absolute autonomous control. Processes are able to be organized absolute decentralized. Nevertheless, consumers might decline these products for privacy concerns, because the tags remain in the clothing. Clothing and parts of it are simple and cheap mass products tagging each part might be too expensive. Additionally, the availability of the required very small smart tags is doubtful and radio range is assumed to be low as well [22], [44].

C. Intelligent Part Scenario

Secondly, tags can be printed or adhesively bonded at each part right after cut out or before cut out (Fig. 16). The tags have the same capabilities as described in the fiber scenario. Parts are identifiable after being programmed by an RFID gate. Machines are tagged and can communicate with the parts.

The scenario is similar to the fiber scenario and uses the total autonomous control architecture as well, but the tagging technology differs. It can prove to be difficult to bond the fabric with tags before cutting parts out, because usually several layers of the fabric are stacked before cut at once. Cutting single layers of fabric is inefficient. A special machine is required to bond the smart tags on the fabric when it is rolled out, or alternatively a stamping machine has to be used after cutting to bond a tag at each part. Further problems might arise during successive operations, because durability of the bonding ties has to be ensured during manufacturing, whereas consumers probably want to wear tag free garments.

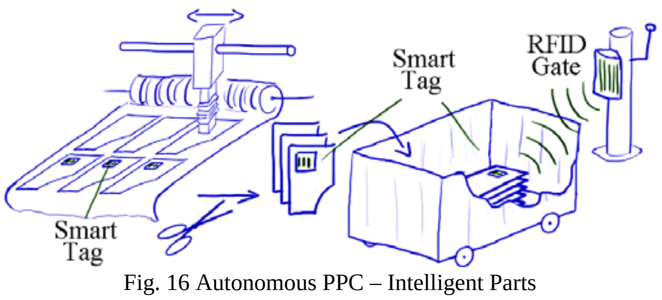

Fig. 16 Autonomous PPC – Intelligent Parts

D. Intelligent Garment Scenario

Third, the ready made garments can be tagged with smart labels when the garment's label is applied at the last product quality check (Fig. 17). The smart tags can be included in the paper labels of jeans garments and can be programmed by an RFID gate.

No acceptance problems are to be expected with consumers, because they can remove the tags with ease. The proposal enables autonomous control in supply chain data management. But there is no use of the tags for manufacturing control, because they are introduced late in manufacturing process.

E. Intelligent Batch Scenario

Different possibilities have been discussed in previous sub-sections to enhance garment pieces or parts with smart tags. Tagging of single parts is very difficult either by lack of very small smart labels or bonding technology, each in combination with consumer acceptance problems. Tagging of readymade garments does not suffer from these problems. But, it solves neither the information problem in manufacturing, nor does it enable autonomous control there.

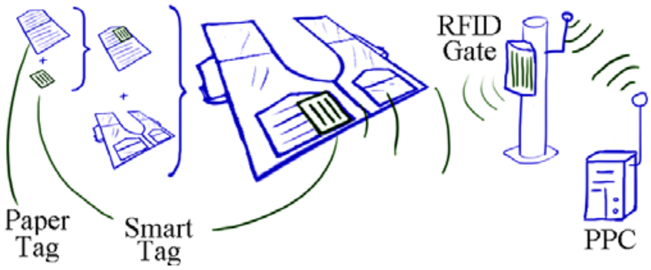

Fig. 17 Autonomous PPC – Intelligent Garment

Tagging of each single garment part at the date of its creation seems to be neither possible, nor affordable today. But it is possible to connect garment parts with transportation units by putting them inside and to tag the box or trolley instead. Such a scenario has the same properties as described in sub-section 5.B and 5.C, if each box carries only one part. However this proposal does not fit manufacturing in the apparel industry well, due to the high number of very different parts that need to be put into boxes. Further, it is not critical for apparel manufacturing control to identify each single part. The complexity of the system architecture would be very high.

It might be sufficient to control small batches of parts instead. The batch itself becomes intelligent, if several parts of the same type are put into a tagged box for transportation purposes. The systems complexity is lower and autonomous control can be applied at the detail level of batches. The number of parts in a box can be adjusted, if necessary in future. The successful application of the intelligent batch scenario depends on the quality of the interfaces used between manual processes and workplaces on the one hand and the tagged devices, like boxes and machines, on the other hand. Fig. 18 shows an approach of autonomous control in apparel manufacturing, which takes into account the previous discussion.

The fabric is cut and the parts are put into an intelligent trolley. The trolley is equipped with a smart box which has a display made of digital paper to show its status as well as product and processing information about the goods inside. Digital paper is basically a robust polymer foil with encapsulated ink balls for each dot. It is a relative cheap display technology with very low power consumption [45]. The trolley is able to count and check the number of parts inside, e.g. by weighing or light barrier. Simple pushbuttons enable human workers to operate the smart box, e.g. to track the amount of parts that are reduced to waste. The information held by the intelligent trolley is updated via wireless communication technology. The trolley does not necessarily need separate energy supply by battery, if the tag is powered by a corresponding communication device, like a RFID reader, or by wireless electricity transmission systems[43]. The trolley is the core enabling device in the batch scenario and can be used highly flexible in the manufacturing process.

Each batch of semi-finished parts is now traceable within the manufacturing process. Nevertheless, caution must be taken by workers, when pushbuttons are used to count parts being put in or removed from the trolleys. The trolley's smart tag employs a certain decision strategy and decides which work place should be used next. Decisions can be made each time the tag is powered, e.g. when it is placed at a wireless energy transmission terminal at the beginning and the end of a working place.

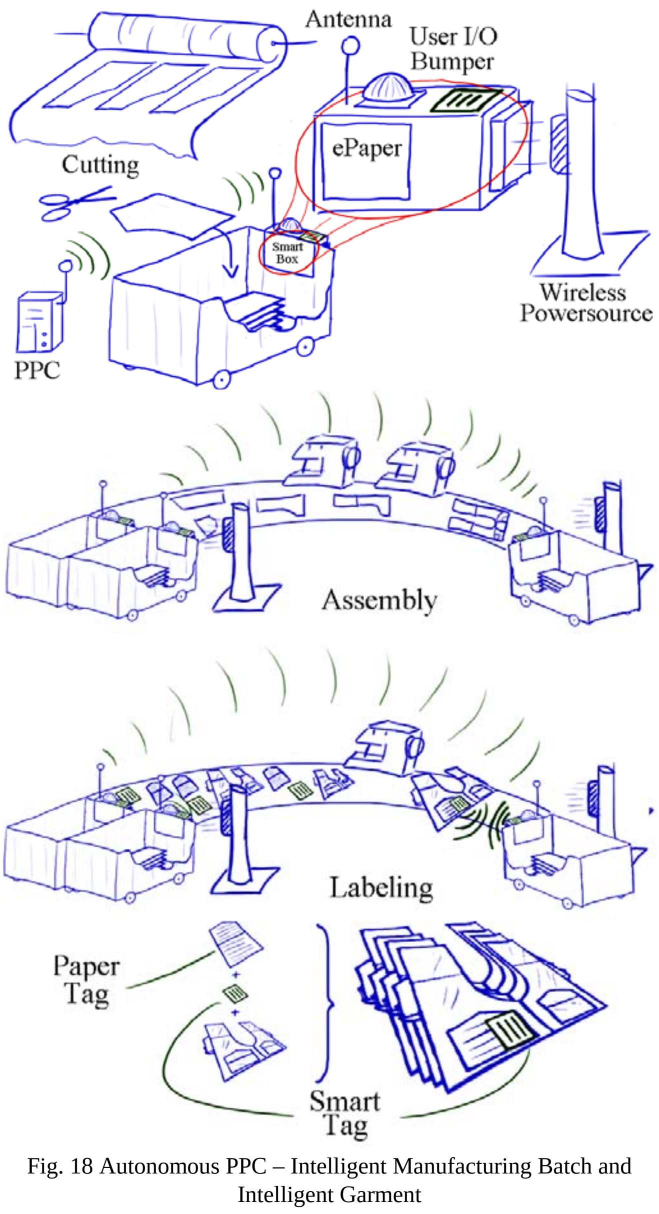

Fig. 18 Autonomous PPC – Intelligent Manufacturing Batch and Intelligent Garment

Quality gates are used to check the product and the process quality. One example is verification of the number of garment parts located in a trolley compared to the number noted at the intelligent label. A trolley being emptied at the beginning of an assembly line can transfer batch related information to a trolley receiving the recently processed parts at the end of that line. Another smart label is plugged at the garment in combination with the paper garment label at the end of the manufacturing process. The batch related information is transferred from the latest trolley to the garment's label.

The combination of all actions allows tracking, tracing and autonomous control of each batch of semi-finished parts at the manufacturing site. Additionally, the final tag at the ready made garment provides the history of each batch's process and enhances each single garment to an autonomous logistic object in the successive supply chain. The process quality can be measured for manufacturing and for the supply chain. Customers are able to comprehend the history of the garments and its quality. The systems complexity is lower than in total autonomous control architecture, if the batch size is bigger than one. The investments are lower as well. The scenario is an implementation of the hub architecture as described in section 3.B, if the batch size is bigger than one. Trolleys and manufacturing lines are hubs for the garment parts in this case.

VI. Conclusion and Outlook

Based on a case study, specific problems of the apparel industry have been denoted. The miscounting of apparel quantity during manufacturing is one of the major sources of errors, which leads to further problems in the successive steps in the supply chain as well. Three different system architectures are discussed for application of autonomous control. A specific hub architecture is proposed to overcome the errors in the case study's scenario. The solution is based on identifiable batches that move autonomously through the manufacturing process. Trolleys and RFID gates provide hub services to the batches and allow easy tracing, counting and book keeping.

Further research has to be carried out to analyze the feasibility of the described scenario in detail with simulation studies and in real apparel manufacturing processes. A closer look has to be taken at the required infrastructure and its configuration, as well as at analyzing costs and benefits of the proposed solution. The impact of the solution to the supply chain should be considered as well.

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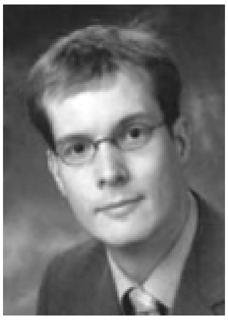

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