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Modular Configuration of an RFID-based Hybrid Control Architecture for a Situational Shop Floor Control

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Abstract: Nowadays, producing companies act in a turbulent environment, which is caused by the globalization of the economy and the continuous shift from seller markets to buyer markets. One central aspect is the demand for customized products at short delivery times and reasonable costs. In this context, shop floor control becomes more and more important and therefore, the complexity of its purposes increases. However, current shop floor information, which is indispensable for a targeted execution of these purposes, is often not available. The RFID (Radio Frequency Identification) technology enables an adequate and situational shop floor control. Since the integration and capabilities of RFID depends on specific framework conditions (e.g. forms of organization), an approach for a modular configuration of an RFID-based hybrid control architecture, that separates control efforts into centralized and decentralized control elements, is motivated. Finally, this approach could be implemented to a use case of a German automotive seat supplier.

Keywords: Production Planning and Control (PPC), Smart Product, RFID, Real-Time Capability

1. Introduction

Today, manufacturing organizations have to face a turbulent environment that is characterized by high complexity and dynamics. As a result of the globalization of the economy and saturated markets, the number of product variants with specific configurations increases and lot sizes and production volumes decrease. Furthermore, adherence to delivery dates becomes more important (Zaeh & Ostgathe, 2009; Koren, 2006). Thus, modern production systems require a high degree of flexibility to produce these products with a high quality and at reasonable costs to remain competitive in the global market (Mehrabi, et al., 2002; Feldmann & Slama, 2001).

Regarding the growing dynamics, shop floor control, which manages the material flows and controls the production activities, is becoming increasingly complex (Poon, et al., 2007; Higuera & Montalvo, 2007). In order to deal with the production of the individual range of products, manufacturers implement a suitable form of organization (e.g. job shop production) for their production system. Regarding the flexibility, each form of organization is characterized by a specific degree of freedom (Huang, et al., 2007; Schuh, 2006). On the one hand, a high degree of freedom of a production system is necessary to cope with the challenges of manufacturing a high number of product variants. On the other hand, flexible production processes are error-prone due to the low repetition rate of processes that is present in the aforementioned production systems (Schuh, et al., 2007). In spite of that, shop floor control methods, which are embedded into individual PPC systems (Production Planning and Control), should realize the production orders and adhere to the delivery commitment. (Scholz-Reiter & Freitag, 2007). The success of the different methods for shop floor control highly depends on real-time data from the manufacturing system, the individual product and the production process. The latter, in particular, needs to adapt continuously to the current shop floor situation (Zaeh & Ostgathe, 2009; Huang, et al., 2008; Schuh, et al., 2007). However, the necessary real-time shop floor information is often not available (Huang, et al., 2007).

Modern sensor technologies, such as RFID (Radio Frequency Identification), that are integrated into shop floor control systems are able to eminently enhance the information management on the shop floor and to realize accurate and situational control decisions (Zaeh & Ostgathe, 2009).

This paper identifies the necessity of separating the control efforts on centralized and decentralized control elements and the potentials of implementing a so-called RFID-based hybrid control architecture. In such control architectures, on the one hand, products are tagged with RFID transponders. On the other hand, a centralized event administration system (EAS) that allows to capture, to provide and to distribute shop floor event data in real-time, is integrated besides conventional PPC systems. Based on these results, a holistic approach for the modular configuration of this architecture that is dependent on the form of organization and the method of shop floor control is presented. An exemplary modular configuration of an RFID-based hybrid control architecture could be adapted to a German automotive seat manufacturer (Figure 1).

Figure 1. RFID-tagged automotive seat (Image sources: www.autoran.de, www.chriscdesign.co.uk)

2. State of the Art

2.1 Architectures of Shop Floor Control

In order to face the aforementioned production complexity, manufacturers have to realize a dynamic adaptability of production processes that provides a high flexibility and robustness against disturbances in manufacturing (Trentesaux, 2009). In this context, the control architecture of the shop floor control system has a huge influence on the performance of a production system (Scholz-Reiter & Freitag, 2007; Bongaerts, et al., 2000).

Traditional approaches of shop floor control architectures, which are utilized e.g. in Computer Integrated Manufacturing (CIM) applications, are hierarchically organized and target the optimum of the global control problem by decomposing it into hierarchically dependent sub-problems. In a centralized shop floor control system, the decisions are made on the supervisory level by the centralized control elements and the control commands are typically top-down (Figure 2, left) (Trentesaux, 2009; Bongaerts, et al., 2000). Therefore, the relationships between centralized and decentralized elements of control are master-slave relationships. Hence, centralized shop floor control architectures are static and deterministic regarding the reactivity to disturbances. Since the response time is low, the production plans become ineffective after a short time on the shop floor. Thus, centralized shop floor control systems do not allow a fast and flexible adaption of the production system (Bongaerts, et al., 2000).

To overcome the disadvantages of centralized shop floor control architectures, decentralized control systems such as multi-agent systems (MAS) were developed (Monostori, 2006; Bongaerts, et al., 2000). In these heterarchical architectures, the control efforts and the decision-making authorities are distributed to local organization units, i.e. decentralized control elements. The global control problem is separated into several control problems that are solved independently by these decentralized control elements without a supervisory control unit (Figure 2, right) (Trentesaux, 2009; Böse & Windt, 2007; Lin & Solberg, 1994). Therefore, decentralized shop floor control architectures are highly flexible and robust against disturbances in manufacturing. However, the decentralized control elements are not able to provide a globally optimized performance. Furthermore, the production system's behavior tends to be unpredictable under this heterarchical control architecture (Bongaerts, et al., 2000).

Hybrid control architectures such as Holonic Manufacturing Systems (HMS) combine the advantages of the hierarchical and heterarchical approaches of shop floor control (Valckenaers & van Brussel, 2005). In these control architectures, the control efforts and the decision-making authorities are properly distributed on centralized and decentralized organization units (Figure 3). Centralized control elements ensure the overall performance optimization and the predictability of the production system. A high flexibility and robustness against disturbances and unforeseen events are offered by the local units of a hybrid control architecture.

Therefore, both, centralized and decentralized control elements, take on the purposes of shop floor control to support the optimization of the production system in regard to the following, partially competitive, logistic objectives (Wiendahl, 2009): high capacity utilization, high adherence to delivery dates, short throughput times and a low WIP (Work-In-Process).

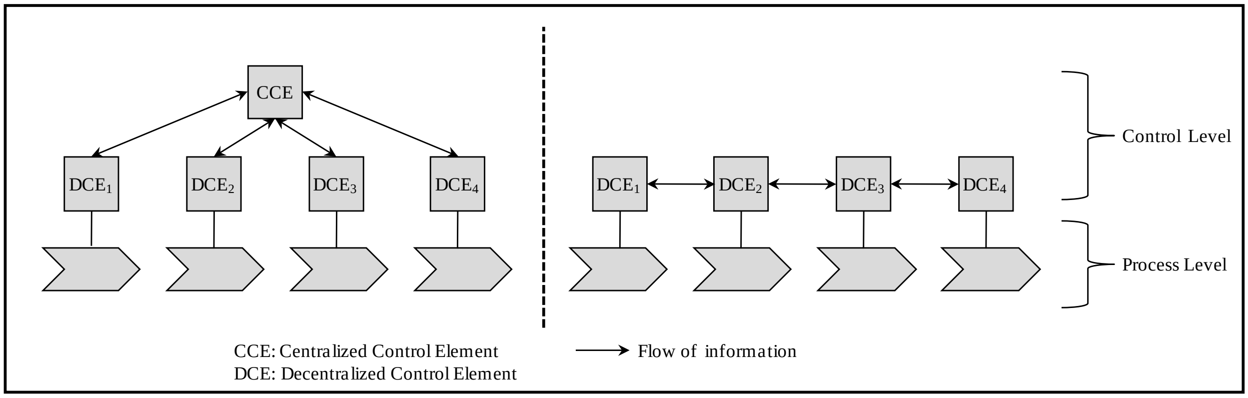

Figure 2. Hierarchical (left) and heterarchical (right) architectures of shop floor control (based on Bongaerts, *et al.*, 2000)

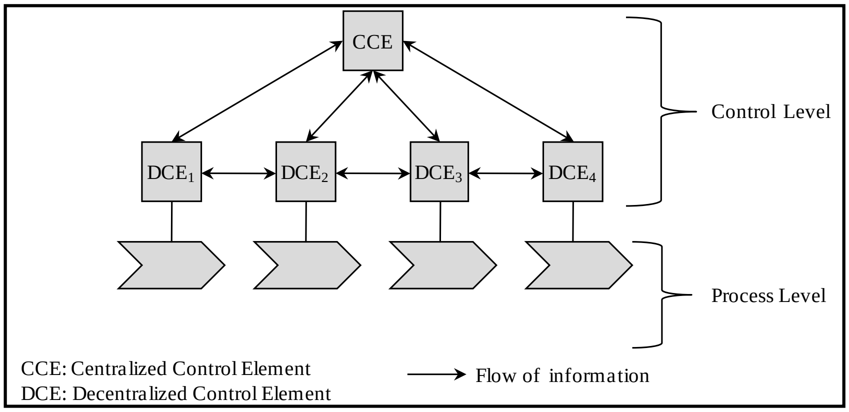

Figure 3. Hybrid architecture of shop floor control (based on Bongaerts, *et al.*, 2000)

2.2 Purposes of Shop Floor Control

The main purposes of shop floor control are the order release, capacity control, sequencing and monitoring of orders. The generation of orders is one of the main purposes of production planning and should be consequently considered separately from the mentioned purposes of shop floor control (Huang, et al., 2007; Lödding, 2005).

The order release defines the transition between planning phase and production phase and triggers new orders to the shop floor based on specific parameters (e.g. planned due dates, available capacities, WIP). These parameters need to be determined on the basis of available shop floor information (Wiendahl, 2009). Furthermore, it is distinguished between centralized (e.g. Manufacturing Resource Planning (MRP II), Constant Work-In-Process (ConWIP)) and decentralized (e.g. Kanban, Paired-cell Overlapping Loops of Cards with Authorization (Polca)) order releasing methods (Schuh, 2006; Lödding, et al., 2003 Suri, 1998) whose capability depends heavily on the quality of the ascertained parameters. The capacity control decides on the actual utilization of resources that differs from capacity planning especially in case of unforeseen machine failures. It determines hereby the overall performance of the production system (Nyhuis, et al., 2009; Lödding, 2005). The purpose of the sequencing is to determine which order in the waiting queue of a work station or work center is processed next. Therefore, every waiting order receives a specific priority dependent on defined criteria of so-called priority rules (e.g. First In – First Out (FIFO), Slack-Time sequencing) (Lödding, 2005). Hence, independent of the implemented priority rule, the decentralized decision-making process eminently requires reliable provision of information about the waiting orders (e.g. order status, delivery date). The order monitoring is essential for an adequate shop floor control, because after releasing the order for being processed, real-time information about the production status of resources and orders as well as the product status is necessary to make reasonable decisions (Huang, et al., 2007).

As a function to the present form of organization, different shop floor control methods are available to support and to manage the explained purposes. The traditional forms of organization are the line production, cellular manufacturing, job shop production and fixed-site production (Groover, 2008, Huang, et al., 2007; Huang, et al., 2006). The capability of these methods differs widely subject to the present form of organization. For example, the degree of freedom regarding the overall flexibility of line productions with strictly directed material flows is low. Therefore, the possibility of shop floor control methods to influence the production processes are heavily limited.

The above discussion has demonstrated the necessity of current shop floor information as a basis for a targeted and situational execution of the purposes and methods of shop floor control. Without this data an optimization of the production system regarding the logistic objectives and an efficient failure management in case of unforeseen events or disturbances (e.g. urgent orders, machine failures) is not achievable by shop floor control systems.

2.3 Integration of Modern Sensor Technologies into Shop Floor Control Systems

After the order release, real-time information is, as aforementioned, indispensable to react to disturbances quickly, to make reasonable and situational decisions and to optimize the production system regarding the logistic objectives (Huang, et al., 2007). Manual log sheets embedded into production data acquisition (PDA) systems are often delayed and defective. So sensor technologies providing real-time data acquisition without human interaction are a promising alternative (Huang, et al., 2006). Modern PDA systems are using such sensor technologies to deliver data about the current shop floor situation (capacity utilization, throughput rates etc.). However, these systems are primarily implemented as decentralized isolated applications and are not embedded into centralized or decentralized planning systems. Thus, the provided PDA data is often used for statistical evaluations but seldom for adaption of production processes (Beckert, et al., 2001).

Auto-ID (automated identification) technologies and especially RFID are indispensable elements to collect real-time data. Superior to other Auto-ID technologies, RFID enables to identify tagged items automatically and contactless. For example, a specific order tagged with an RFID transponder is acquired through a unique identification number, the item ID, on the product. By combining products with RFID transponders, they become so-called smart products. Furthermore, it is possible to store data on these smart products as well as to read it (Huang, et al., 2008; Finkenzeller, 2003). The potentials for the integration of the RFID technology into production systems can be structured into three capability levels (Figure 4) (Huang, et al., 2008). The first capability level is the automatic identification of items, i.e. components or products, with the help of RFID identification points along the material flow. The identified item ID can be linked to relevant information provided by centralized or decentralized elements of shop floor control. RFID integration on the second capability level allows tracking and tracing of orders. The basis for this is the identification of items at characteristic shop floor positions (e.g. start of production). Thus, released orders can be monitored in real-time and an exact image of the current shop floor situation can be provided. The third capability level of RFID integration exploits the opportunity to write product-specific data on the RFID transponder. Therefore, product-specific data is provided at the relevant point of action near real time and processes can be controlled locally. The product memory supports the efficient execution of the purposes of shop floor control and enables hereby adaptive shop floor control by product-resource communication (Schuh, et al., 2011; Brintrup, et al., 2010; Zaeh & Ostgathe, 2009).

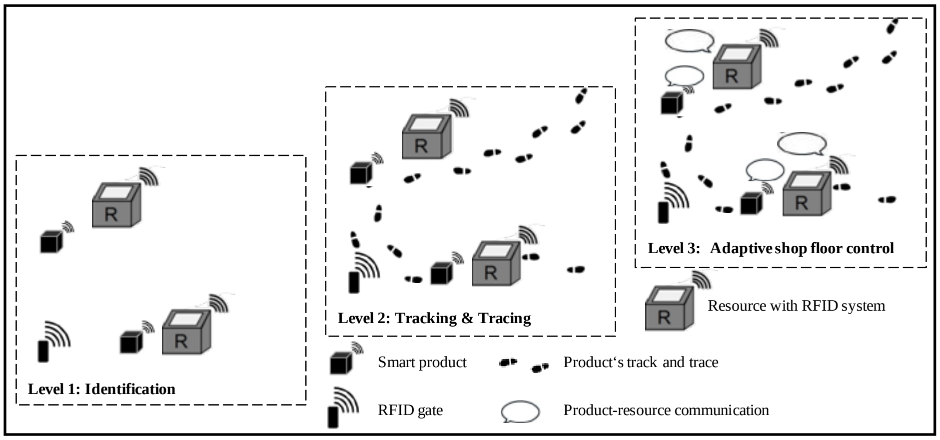

Figure 4. Capability levels of RFID integration

The third capability level of RFID integration, an adaptive shop floor control, offers promising possibilities to ensure a high flexibility and adaptivity of production processes by providing proper information at the proper time, at the proper place and in the proper quality. However, the third capability level is not suitable for every production system. This suitability depends, as mentioned above, on the production system's degree of freedom determined by the present form of organization and the chosen methods of shop floor control. Consequently, an approach of a modular configuration of an RFID-based hybrid control architecture is motivated.

3. Approach for a Modular Configuration of an RFID-based Hybrid Control Architecture for a Situational Shop Floor Control

As discussed in Section 2, the provision of real-time data enabled by the integration of RFID presents a promising approach to enhance the information management on the shop floor and to realize accurate and situational decisions of control. From the global perspective, the following concept of an RFID-based hybrid control architecture aims on reducing WIP and throughput times by improving adherence to delivery dates and capacity utilization.

3.1 Relevant Data Types in RFID-based Hybrid Control Architectures

An established approach to structure the relevant data of a production system is the classification of product- (e.g. geometric shape), process- (e.g. NC codes) and resource- specific (e.g. resource status) data (Zaeh, et al, 2010). Additional to product-specific data stored on an RFID transponder, order-specific event data plays an essential role within the presented approach of an RFID-based hybrid control architecture. The capturing (e.g. via PDA systems) and provision of process- and resource-specific data are embedded into conventional PPC systems. An RFID-based hybrid control architecture provides a combined data management of product-specific data, carried with the individual smart product, and order-specific event data that is utilized by an EAS.

The basis for the generation of order-specific event data is the identification of items, i.e. components or products, at characteristic shop floor positions or particular instants of time (e.g. start of production, end of quality assurance). An order-specific event is an RFID read event that aggregates real-time information about the time, the place and the reason of a particular item identification. For reasons of standardization, it is suitable to structure the events by the standards of the EPC Information Service (Tamm & Tribowski, 2010). The so called EPCIS events are generated locally and utilized by a centralized EAS for enhancing the shop floor information management and for an event-based synchronization of production processes. However, EPCIS events are not able to describe product-specific data and the real-time provision of this data by conventional PPC systems is not realizable in an efficient manner. Therefore, the RFID transponder on the product can be used to provide product-specific data at the relevant point of action.

Product-specific data, carried with the smart product, includes organizational and processual information. Organizational product-specific information (e.g. item ID, order number) is needed for unique order identification on the shop floor. Processual product-specific information can be carried with the individual product to be considered in relevant steps of the production process or shop floor control (e.g. quality data (failure codes etc.), additional order information (delivery date etc.) (Zaeh & Ostgathe, 2009).

3.2 Centralized and Decentralized Elements of Shop Floor Control

An RFID-based hybrid control architecture follows the aforementioned concept of hybrid architectures that distributes the control efforts on centralized and decentralized control elements (Reinhart, et al., 2011).

As centralized elements of shop floor control, conventional PPC systems are implemented as global organization units into the shop floor control architecture. Centralized methods of shop floor control, for example, are embedded into and executed by these PPC systems. They are able to ensure the overall performance optimization because of the global decision-making authority. Moreover, an EAS, as further centralized element of shop floor control, allows the capturing, provision and distribution of the aforementioned order-specific event data in real-time. The captured EPCIS events can be used by an EAS for an event-based synchronization of production processes and by the PPC systems to monitor released orders, to provide an exact image of the current shop floor situation and to make situational decisions.

Decentralized elements within an RFID-based hybrid control architecture are local organization units of work stations or work centers, such as operators or decentralized shop floor and process control systems. Smart products enhance the information basis of both, centralized and decentralized decision-making authorities. On the one hand, the generation of real-time order-specific event data is utilized and administrated by the EAS and therefore, by centralized PPC systems. On the other hand, additional product-specific data carried with the individual smart product can be considered in specific production processes (e.g. quality data) and decentralized shop floor control decisions such as sequencing of orders (e.g delivery date). Consequently, the smart product is able to actively influence shop floor control decisions and act as an additional element of control in production processes (Figure 5).

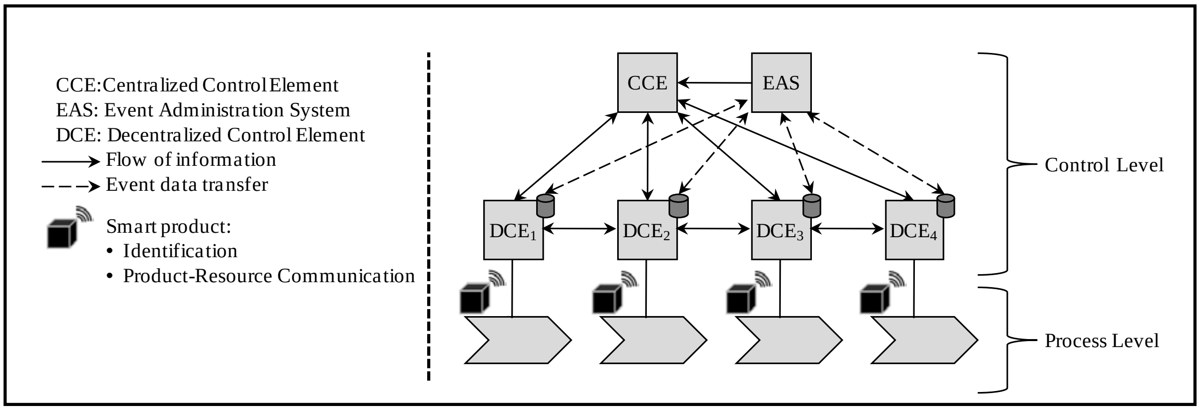

Figure 5. RFID-based hybrid control architecture

3.3 Capabilities and Modular Configuration of an RFID-based Hybrid Control Architecture

An essential control element of an RFID-based hybrid control architecture is the smart product. Therefore, the capability levels of RFID integration, as a function of the production system's degree of freedom determined by the present form of organization and the chosen methods of shop floor control, can be transferred on the implementation of these architectures.

On the first capability level, the automatic item identification, identified products can be linked to relevant order information. Centralized (e.g. order release) and decentralized (e.g. sequencing) shop floor control decision-making can be supported. However, above all, the first capability level can streamline and protect production processes by substituting manual identification processes (e.g. barcode scanning) by a higher degree of automation. For example, order numbers of matching components can be automatically compared before they get assembled and hereby, false assembly can be avoided. The first capability level of RFID integration is particular suitable for forms of organization with a low degree of freedom (e.g. line production).

An RFID-based hybrid control architecture on the second capability level includes the integration of an EAS and allows the tracking and tracing of orders. On the one hand, the generated order-specific events can be used, as mentioned, to provide an exact image of the current shop floor situation. Hence, parameters such as WIP can be ascertained near real-time and decision-making authorities operate on a reasonable information basis to properly execute the purposes of shop floor control (e.g. release of orders, capacity control). On the other hand, order-specific events allow for the synchronization of production processes. The implementation of event-based decentralized control loops can eminently reduce centralized control efforts. In this context, for example, released orders are able to trigger the timely pre-assembly of required order-specific components. Hence, the implementation of an EAS is suitable for production systems that are characterized by flexible material flows (e.g. job shop production).

An RFID-based hybrid control architectures on the third capability level provides the basis for an adaptive planning and shop floor control by storing additional data on the RFID transponder. This level is qualified for production systems that are characterized by a high flexibility and complex material flows. The smart product, as decentralized control element, is able to actively influence "its" production process. Dependent on the character of the product-specific data the degree of adaptivity can be defined. For instance, if the product-specific delivery date is written on the transponder, it can be used to support the decentralized sequencing of orders. The consideration of product-specific quality information or tolerance data in production processes is able to avoid waste.

The approach of an RFID-based hybrid control architecture combines the advantages of hierarchical and heterarchical control architectures. On the one hand, smart products enhance the information quality on the shop floor to make decentralized decisions. On the other hand, the implementation of a centralized EAS with decentralized identification points allows for the real-time creation of a reasonable image of the shop floor situation as information basis for control decisions and control loops. Since the capabilities of an RFID-based hybrid control architecture is dependent on the degrees of freedom of the production system, a modular configuration of such an control architecture is required. The configuration bases on the characteristic of the correlative input modules, i.e. present form of organization and chosen methods of shop floor control, of the specific production-system. In summary, the objective of this modular configuration is to provide a set of input modules (e.g. job shop production, ConWIP order release, slack sequencing) for the implementation of such a control architecture in a specific production system. On the basis of this set, the determination of relevant modules for this production system is performed and the suitable capability level of RFID integration can be deduced. Consequently, the specific RFID-based hybrid control architecture can be modularly configured (e.g. number of identification points, definition of additional product-specific data on the smart product). Finally, dependent to this configuration, the benefits of a specific implementation can be exploited.

4. Use Case of the Automotive Industry

The approach for a modular configuration of an RFID-based hybrid control architecture could be adapted to a German automotive supplier. This supplier manufactures high variant vehicle seats in a combined line production consisting of several manual or partly automated, loosely linked assembly and pre-assembly lines. The production program provides two fundamental distinct variants (v1 and v2) with different production volumes, degrees of added value and throughput times. Therefore, the final seat assembly of these two variants is separated into two parallel assembly lines, whereas the backrest and other sub-assemblies are delivered by non-variant specific assembly lines that provoke a high material flow complexity. Hence, an additional challenge of this complex material flow is the pre-defined delivery sequence that needs to be ensured during the assembly process. In this context the main purposes of shop floor control order release and sequencing are fulfilled by a load-oriented ConWIP and a FIFO sequencing.

Based on this initial situation, relevant modules (combined line production, load-oriented ConWIP, sequencing by FIFO) could be determined. Since the material flows in a combined line production are not strictly directed and the production processes of high variant seats are complex, an RFID integration on the third capability level could be deduced. The modular configuration and the benefits of this RFID-based hybrid control architecture can be demonstrated as follows: The centralized elements of shop floor control are a conventional MES (Manufacturing Execution System) that executes the purposes of shop floor control and an integrated EAS. This EAS enables situational event-based control decisions. Decentralized elements of shop floor control are tagged backrests and seats. These smart products carry and communicate product-specific organizational information (order numbers) and processual product-specific quality data (order status, failure code, tolerance data) at the relevant point-of-action. Several RFID identification points could be defined, with the result that order-specific events are generated at particular shop floor positions (e.g. end-of-line (EOL)). These events allow for a high transparency of the current shop floor situation and therefore decentralized control loops. A new order gets released by the MES on the basis of an order-specific event, which is generated at the moment of the faultless EOL quality assurance of a completed seat. The described decentralized control loops on the basis of order-specific events, for example between seat structure assembly and backrest assembly, are able to synchronize production processes. Thus, waiting times and buffers could be reduced. The quality data on the product (order status) enables, in case of a production disturbance, a direct routing of faulty orders into the re-work center. The re-work processes could be controlled and accelerated by decentralized provision of the failure code and the real-time order-specific events. Furthermore, the seat assembly into a vehicle at the OEM (original equipment manufacturer) could be supported by the decentralized, real-time provision of tolerance data that is stored on the RFID transponder of the seat. Consequently, the production system of this seat assembly could be optimized regarding throughput times, capacity utilization and adherence to delivery dates.

5. Summary

In this paper, the advantages of hybrid shop floor control architectures and the challenges for manufacturing a specific number of product variants in certain production volumes are demonstrated. To resolve those challenges, several suitable forms of organization and methods for shop floor control are mentioned. A lack of adaptability and flexibility concerning disruptions is identified and the insufficient provision and consideration of real-time shop floor information in conventional PPC systems is presented. Hence, an approach of an RFID-based hybrid control architecture is motivated. This control architecture enhances current shop floor control systems by integrating the RFID technology and an EAS that allows real-time acquisition and provision of manufacturing data. Since the presented capabilities of an RFID-based hybrid control architecture depend on the present form of organization and the chosen methods of shop floor control, a modular configuration is proposed and will be completed in further research. Beyond that, the benefits regarding the logistic objectives and the technical feasibility of the presented approach will be evaluated by different simulation models and a prototypical implementation in a realistic demonstration platform.

6. References

Beckert, B., & Hudetz, W. (2002). State and potential of production data processing (in German). *PPS Management,* 2, 35-39.

Bongaerts, L., Monostori, L., McFarlane, D., & Kádár, B. (2000). Hierarchy in distributed shop foor control. *Computers in Industry,* 2,123-137.

Böse, F., & Windt, K. (2007). Catalogue of Criteria for Autonomous Control in Logistics, In M. Hülsmann & K. Windt (Eds.), *Understanding autonomous co-operation and control in logistics: The impact of autonomy on management, information, communication and material flow* (pp. 57-72). Berlin, Germany: Springer.

Brintrup, A., Ranasinghe, D., & McFarlane, D. (2010). RFID opportunity analysis for leaner manufacturing. *International Journal of Production Research,* 9, 2745-2764.

Feldmann, K. & Slama, S. (2001). Highly flexible Assembly - Scope and Justification. *Annals of the CIRP*, 2, 489-498.

Finkenzeller, K. (2003). *RFID handbook. Fundamentals and Applications in Contactless Smart Cards and Identification*. Hoboken, NY, USA : John Wiley & Sons.

Groover, M. P. (2008). *Automation, Production Systems and Computer Integrated Manufacturing*. Upper Saddle River, NJ, USA: Pearson Education.

Higuera, A. G., & Montalvo, A. C. (2007). RFID-enhanced multi-agent based control for a machining system. *International Journal of Flexible Manufacturing Systems,* 1, 41-61.

Huang G. Q., Zhang, Y. F., & Jiang, P. Y. (2007). RFID-based wireless manufacturing for real-time management of job shop WIP inventories. *International Journal of Advanced Manufacturing Technology,* 7-8, 752-764.

Huang, G. Q., Wright, P. K., & Newman, S. T. (2008). Wireless manufacturing: a literature review, recent developments, and case studies. *International Journal of Computer Integrated Manufacturing,* 7, 579-594.

Huang, G. Q., Zhang, Y. F., & Jiang, P. Y. (2006). RFID-based wireless manufacturing for walking-worker assembly islands with fixed-position layouts. *Robotics and Computer-Integrated Manufacturing,* 469-477.

Koren, Y. (2006). General RMS Characteristics. Comparison with Dedicated and Flexible Systems. In A. I. Dashchenko (Ed.), *Reconfigurable Manufacturing Systems and Transformable Factories* (pp. 27-45). Berlin, Germany: Springer.

Lin, G. Y., & Solberg, J. J. (1994). Autonomous control for open manufacturing systems. In S. B. Joshi & J. S. Smith (Eds.), *Computer Control of Flexible Manufacturing Systems*(pp.169-205). London, UK: Chapman & Hall.

Lödding, H. (2005). *Methods of Production Control* (in German). Berlin, Germany: Springer.

Lödding, H., Yu, K.-W., &Wiendahl, H. -P.(2003). Decentralized WIP-oriented manufacturing control (DEWIP). *Production Planning & Control,* 1, 42-54.

Mehrabi, M. G., Ulsoy, A. G., Koren, Y., & Heytler, P. (2002). Trends and perspectives in flexible and reconfigurable manufacturing systems. *Journal of Intelligent Manufacturing,* 2, 135-146.

Monostori, L., Váncza, J., & Kumara, S. R. T. (2006). Agent-Based Systems for Manufacturing. *Annals of the CIRP,* 2, 697-719.

Nyhuis, P., Münzberg, B., & Kennemann, M. (2009). Configuration and regulation of PPC. *Production Engineering Research and Development,* 3, 287-294.

Poon, T. C., Choy K. L., & Lau, H. C. W. (2007). A real-time shop-floor control system: an integrated RFID approach. *International Journal of Enterprise Network Management,* 4, 331-349.

Reinhart, G., Engelhardt, P., Genc, E., Niehues, M., & Ostgathe, M. (2011). Planning and Control of Processes in Production (in German). *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb,* 5, 326-331.

Scholz-Reiter, B., & Freitag, M. (2007). Autonomous Processes in Assembly Systems. *Annals of the CIRP,* 2, 712-729.

Schuh, G. (2006). *Production Planning and Control* (in German). Berlin, Heidelberg, Germany: Springer.

Schuh, G., Stich, V., Brosze, T., Fuchs, S., Pulz, C., Quick, J., Schürmeyer, M., & Bauhoff, F. (2011). High resolution supply chain management: optimized processes based on self-optimizing control loops and real time data. *Production Engineering Research and Development*.

Schuh, G., Gottschalk, S., & Höhne, T. (2007). High Resolution Production Management. *Annals of the CIRP,* 1, 439-442.

Suri, R. (1998). *Quick response manufacturing: a companywide approach to reducing lead times*. Portland, OR, USA: Productivity Press.

Tamm, G. and Tribowski, C. (2010). *RFID. Informatik im Fokus*. Springer, Berlin, Germany.

Trentesaux, D. (2009). Distributed control of production systems. *Engineering Applications of Artificial Intelligence, 7:* 971-978.

Valckenaers, P and van Brussel, H. (2005). Holonic Manufacturing Execution Systems. *Annals of the CIRP, 1:* 427-430.

Wiendahl, H.-H. (2009). Adaptive Production Planning and Control – Elements and Enablers of Changeability. *Changeable and Reconfigurable Manufacturing Systems* (Ed.: H.A. Maraghy).Springer, London, UK, 197-212.

Zaeh, M. F. and Ostgathe, M. (2009). A Multi-agent supported, Product-based Production Control. *Proceedings of the 7th IEEE International Conference on Control*, 2376-2383.

Zaeh, M. F.; Ostgathe, M. and Wiesbeck, M. (2010). Holonic Data Model for Cognitive Production Systems (in German). *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 4:* 309-315.

This is an extended version of a conference paper presented at the 16th International Conference on Industrial Engineering - Theory, Applications, and Practice, 2011, Stuttgart, Germany.