Product-Mediated Communication through Digital Object Memories in Heterogeneous Value Chains

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Abstract—**Industrial production and supply chains face an increased demand for mass-customization and tightening regulations for the traceability of goods, leading to higher requirements concerning flexibility, adaptability and transparency of processes. Technologies for the "Internet of Things" such as smart products and semantic representations pave their way into future factories and supply chains to fulfill these challenging market demands.**

In this paper a backend-independent approach for information exchange in open-loop processes based on so-called digital object memories (DOM) is presented. By storing order-related data via smart labels on the item, relevant life cycle information is attached to the product itself. This way, information handover via several stages of the value chain with potentially different stakeholders including manufacturer, distributor, retailer, and end customer has been realized. To summarize first best-practice experiences regarding memory structure and content, a prototype implementation based on a scenario of processing dietary supplements in an adaptive process is illustrated.

Keywords- Digital Object Memory, Internet of Things, Distributed Systems, Identification Systems, Radio Frequency Identification.

I. INTRODUCTION

In the economy of the 21st century, the industrial production and distribution of goods face a wide range of so far unknown challenges. Due to globalized markets and higher competition, innovation and production life cycles are continually shortening, e.g. the average development time for consumer goods like a mobile phone dropped from about 18 months in the year 2002 [1] down to 4 months in 2004 [2]. This trend is intensified by a growing market demand for frequent product updates and increasingly customized goods. Today, a modern middle class car is available to the customer in a multitude of variations [3]. Especially in the field of upscale quality products, perishable goods or healthcare products, the above mentioned tendency is supplemented by increasing requirements for a better traceability of products, from the customer as well as from the legislative side [4].

In order to react appropriately to such challenges, current processes in the production industry and corresponding value chains need to become far more adaptable to changing market demands in order to be still profitable and efficient. Additionally, an increased amount of transparency must be provided to satisfy customer and regulatory demands for knowledge about the origin and history of a product.

Promising solutions to meet these challenges seem to be provided by technologies for the "Internet of Things" [5]. Especially auto-ID technologies like barcode and radio frequency identification (RFID) are entering factory systems and logistic chains in a growing extent, bridging the gap between the physical flow of goods and the digital flow of information [6, 7].

Still mainly used for the identification of real world objects by a unique ID to relate them with digital information in a backend system, technologies like barcode and RFID have proved their potential to significantly increase flexibility, transparency and robustness of processes in various domains [8, 9]. Prominent examples for the use of auto-ID technologies can be found in production, logistics and retail applications, ranging from RFID-based production systems [10], via automated airport baggage handling systems [11] to the tracing of products in the retail domain [12].

What most of the current solutions have in common is the comparatively narrow use of auto-ID technologies and related information in closed-loop processes of a single domain or even a single company [11]. Reasons for that are the reuse of attached tags due to cost considerations and the fact that proprietary hard- and software is developed to satisfy varying requirements concerning read/write processing, data transfer bandwidth and data formats every domain has with respect to auto-ID solutions [11, 13]. This results in the fact that in most of the systems currently in operation no auto-ID-based information exchange takes place between different stakeholders of the value chain.

As a first step to solve the problem of consistent information exchange between different domains in heterogeneous open-loop processes, initiatives like EPC GLOBAL[1] or GS1[2] offer solutions to use an object ID (stored

[1] www.epcglobalinc.org

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on a RFID transponder or in a barcode) to access object-related information in a server accessible by different stakeholders of the value chain [14, 15, 16]. Nevertheless, the solution is characterized by a high backend dependency and offers comparatively limited options to continuously store and access product-related life cycle data in real-time. Furthermore, this idea comes basically from the logistics and retail domain and does not reflect typical requirements coming from the manufacturing industry regarding auto-ID for process monitoring and control.

A more holistic and flexible approach to associate digital information items with physical objects is represented by the concept of so-called digital object memories (DOM) [13, 17, 18]. Going beyond current real life auto-ID applications, DOM comprise the organization of object-related information in a memory-like structure. They are created by gathering and storing information from various sources like sensors in the environment or processes a physical object participates in.

II. Motivation

Since the idea of a DOM is not completely new, there are some research projects dealing with the idea of a DOM that will be reviewed subsequently. After that, the focus of this paper will be explained, namely the application of DOM in production processes in conjunction with the whole life cycle of the product.

A. Related Work

Examples for research projects concerned with the creation of DOM are *SPECTER* [19] or *SharedLife* [20]. In *SPECTER*, an artificial memory is utilized to record user interactions with the environment. Reflecting past experiences, the memory can be used to deliver ad-hoc assistance in a CD shopping scenario by triggering situation-aware mechanisms. *SharedLife* drives this idea even one step further by allowing for automatic capturing, sharing, and exploitation of cooking experiences through DOM in a *SmartKitchen* environment [20].

As other implementations of the discussed memory concept show, DOM can vary in several dimensions. The physical storage for instance can be located directly on the object itself [11] or in an external database in the environment [19]. Its implementation can be characterized by a more hardware based implementation [21] or by solutions that are almost entirely software based [22]. The content of DOM varies from personal experiences [20] up to product information and specifications [23]. Potential applications range from personal purposes [24, 25] over assisted living scenarios [26] to healthcare [27, 28] and retail applications [29].

The concept of DOM does not only hold for implementations with a comparatively narrow application focus but also for gathering life cycle information in a broader sense [23]. By accompanying a smart pizza packaging through selected stages of its life cycle, the authors proved that DOM are a viable way to store object-related information for decentralized applications of different stakeholders of a value chain.

Furthermore, Schneider and Kröner [23] state that the most appropriate location for a DOM would be the object itself. Reasons for that are the accessibility of memory content without the need to connect to a backend system and the possibility to track and trace objects on item level, describing requirements that are especially important for applications in industrial processes.

B. Focus of the Paper

With regard to the state-of-the-art concerning gathering and storing object-related information, this paper further elaborates on the use of DOM throughout the life cycle of a product focusing on the production part of the value chain (see Fig. 1). An on-product memory solution will be presented allowing for the storage and exchange of product- and production-related information in open-loop factory processes for production parameterization and product tracing as well.

The paper is organized as follows: First the requirements the DOM has to fulfill will be discussed, followed by a proposal of a concrete design of the DOM including its architecture and content. After that, an example of use will be presented in which several companies are involved in the life cycle of a product. Subsequently, the manufacturing process and the technical setup of the hardware prototype will be described. Based on the object-related information processing in the hardware prototype and the real-life implementation, potential benefits resulting from the adoption of DOM in the manufacturing domain as part of the value chain are highlighted. After this, the challenges one has to face concerning the elaboration of the idea of DOM in order to profit from the mentioned benefits will be discussed. The paper concludes with a summary and an outlook on future research topics to be addressed.

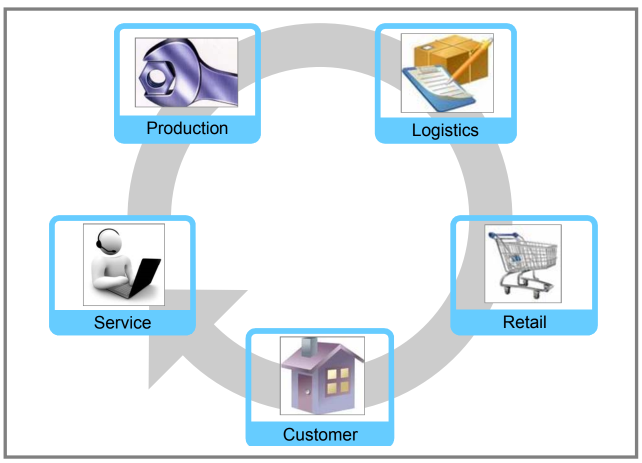

Figure 1. The value chain of a product with focus on its fabrication in an open-loop production process.

III. The Digital Object Memory

How beneficial the application of DOM is depends heavily of its implementation. Thus, first the general requirements have to be clear, before designing an optimal specification of the DOM.

[2] www.gs1.org

A. Basic Requirements

A DOM has to fulfill certain prerequisites in order to allow for the provision of value-added services throughout the fabrication of a product and beyond in later stages of its life cycle. Some of the most essential ones are the following:

Sufficient on-product storage space: Some product- and especially production-related information ask for a physical storage directly on the item. An option to store a certain amount of data on-product must be offered.

Expandability of the memory: The entity of product-related information can be very comprehensive. A solution solely based on on-product data storage is not considered to be sufficient. The option to extend a DOM by referencing the product with information in an off-product storage (e.g. a server in the environment) must be provided.

Fast read/ write access to information: Memory content changes during processes and over time. To update product-related information, both on- and off-product parts of the memory must be rewritable. As manufacturing processes are often characterized by short cycle times, parameters like response time and transfer bandwidth need to be specified.

Use of interoperable and standardized hardware: In industrial applications, reliability and operational availability are highly important. A memory solution has to be realized with state-of-the-art sensor and transponder hardware in order to develop a solution applicable in a real-life factory.

Implementation of a low cost, lightweight memory with small shape factor: The product stands in the foreground, not the technology making it smart by enabling DOM functionality. Costs for memory hardware can only be a split of the original product costs. Solutions comprising on-product sensors that ask for additional processing power and energy supply are not viable.

Flexible memory architecture and data structure: Several manufacturers and sub-contractors contribute to a final product. Architecture and data structure of a DOM must reflect requirements of participating stakeholders' processes regarding the integration of common as well as proprietary product production-related information into a given DOM.

Based on the above mentioned requirements, a concept for a digital object memory will be developed.

B. Object Memory Design and Content

In this section the architecture, data structure and content of the developed DOM will be described in respect of the above mentioned requirements. Following [13] a DOM can be regarded as a general-purpose repository for object-related information. Furthermore, this information can either reside on the smart item itself or be stored on a server simply being referenced by an ID (via barcode or RFID label) on the item.

Having a look at the life cycle of a real product, it becomes obvious that the emerging information – reaching from product specifications, production parameters and sensor readings up to maintenance information and complete handbooks for customer support – will become abundant. Even by applying Moore's law to the miniaturization of storage hardware it will not be possible to store such huge amounts of data on-product in the near future. Therefore the question which information should reside on-product and which can be stored off-product becomes a crucial one for DOM design. One answer to that question could be that DOM information utilized in time critical processes asking for immediate access within milliseconds like manufacturing processes do is a good candidate for on-product residence. The following aspects contribute even more to that point of view:

Firstly, the production of a product comprises an exactly determined number of single process steps and input parameters. Thus, the required amount of on-product storage space to realize memory driven functions becomes determinable as well.

Secondly, input parameters for industrial processes often comprise only a few bits of binary information allowing for the control of even a complex production line by comparatively limited on-product storage space available.

In contrast to that, logistics information like temperature or shock sensor readings is continually growing over time, meaning that the storage space necessary to keep that information heavily depends on transportation time. Thus, it becomes far less determinable, disqualifying itself for on-product storage. The same accounts for product or customer information like PDF or picture files. As this information may be very large, the comparatively limited on-product part of a DOM is deemed to be insufficient at present and the near future as well. Another reason for storing such information on a server in the environment is the fact that access to it is not as time critical as it accounts for process related information in manufacturing systems.

In order to reflect the mentioned considerations, the architecture for the developed DOM follows a hybrid approach (see Fig. 2). The memory content can be directly accessed via a hardware interface by a PLC or a supervisory process control application guaranteeing for minimal lead times and absolute independency from backend systems.

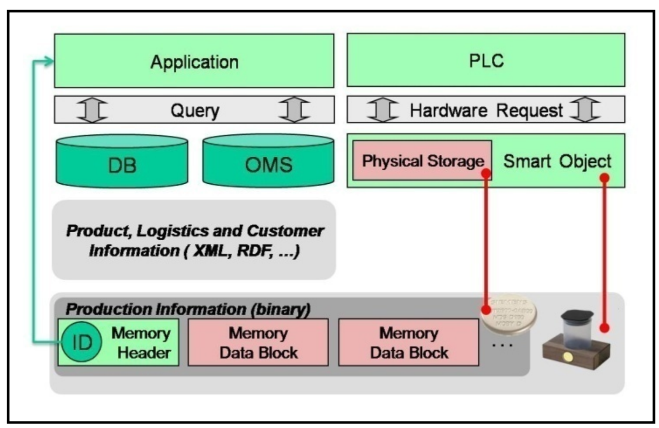

Figure 2. Hybrid Architecture of the DOM with physical on-product storage and off-product database (DB) and/ or object memory server (OMS) referenced by an ID.

To provide a DOM approach which will work during the whole life cycle of a product, the memory is made extendible by an ID physically stored in the on-product DOM as well. Through this ID, applications of various kinds will be able to get access to not limited off-product storage spaces like databases or an object memory server (OMS). Therefore, less time critical information generated trough logistic processes (e.g. sensor readings, transportation information) or utilized during customer interaction (e.g. product specification and additional customer information) can be easily integrated into the DOM of a product. Following this approach the physical object itself is in the center of all interaction and information exchange with its DOM. As this paper concentrates upon the use of DOM in a manufacturing context, it will focus on the implementation and content of the on-product data structure. For information about off-product DOM and their optimal design, the interested reader is referred to [e.g. 19, 20, 21, 23].

IV. The Example of Use

The presented implementation of the DOM will now be applied in an example of use. The regarded example scenario concentrates on a customized *smart drug case* (see Fig. 3) being processed in six steps starting from the initial order placement and finishing with the final delivery of the product at the end.

Consisting of a variety of pre-produced casing parts on the one hand and an individual mixture of dietary supplements on the other hand, the product is a good example that represents the modern fabrication paradigm including a heterogeneous structure of component suppliers and sub-contractors.

The story begins with the initial production of a wooden carrier for the *smart drug case* (already equipped with a DOM) at supplier number one. In a next step, the assembly of the wooden carrier and a little plastic capsule constituting the complete smart product is conducted at supplier number two. In a third step, the customized *smart drug case* is filled with an individual mixture of a variable number of three different dietary supplements. Downstream processes comprising product logistics, retail distribution, customer interaction, and service are also part of the scenario but not regarded in this paper.

The product in the center of the presented scenario is a *smart drug case* that can be individually configured by a potential customer. Physically, the product consists of a wooden carrier and a plastic capsule. For the carrier, two different sorts of wood are available. Furthermore, a potential customer can choose between different logos (e.g. project logo or logos of different research partners) being milled into the carrier. In addition to that, the necessary milling process comprises the manufacturing of the cavity for placing the plastic capsule on the carrier. Besides the casing of the product, its content (dietary supplement pills) can be individually varied. A potential customer can choose from three different dietary supplements and configure an individual mixture up to five pills per smart drug case. Regarding the richness in variations offered by the configuration options for product casing and contents as well, the *smart drug case* is a good example for a highly diversified real-life product.

Figure 3. The *smart drug case* consisting of a wooden carrier (with MDS D160 transponder and project logo on the bottom side) and plastic capsule filled with dietary supplements.

V. Manufacturing Process of the Smart Drug Case

During its life cycle, the *smart drug case* comes into contact with various devices and systems potentially interacting with its DOM. This starts with its manufacturing in intelligent production facilities like the *SmartFactory*^{KL} [3] [30] or the SIEMENS *SmartAutomation* facility [31], continues with its shipment through intelligent logistic processes [30, 31, 32, 33], includes handling in an instrumented retail store [12, 29, 32] and finally ends in the direct interaction with the end customer having a look at the history of the product before using it.

Although each stage of a product's life cycle offers the chance to create value-added services by combining its DOM with the environment's sensing, processing and acting capabilities, a product's manufacturing seems to be the most interesting and complex one. This phase in the lifetime of a product is vivid and especially rich in interaction with its environment, determining a product's characteristics and being crucial for its later performance. Creating new paradigms in production by introducing DOM to that field appears to be especially beneficial. Therefore, the rest of this section will focus on the fabrication of the *smart drug case* within a modular manufacturing process. After giving a short introduction to the manufacturing process and the incorporated production modules, conducted implementation work will be presented by means of the mobile module of the *SmartFactory*^{KL} (see Fig. 4). Downstream processes like product handling, logistics, or customer interaction can also be realized with the presented DOM architecture, data structure, and content, but will not be further elaborated in the presented work.

The fabrication of the *smart drug case* is arranged in a production process of modular style. Each of the three production steps (milling, assembling, filling) is conducted in a production module of a different partner company participating in this research. All modules operate independently from each other and use significantly different hard- and software components to realize the necessary functionality to produce the desired product. The only communication interface to exchange information is given by the on-product memory. The modules are equipped with RFID read/ write systems and a user interface allowing

[3] www.smartfactory.eu

a customer to place an order and to configure a customized drug case. Each production of a sample product starts with the assignment of such an order at one of the production modules. After defining the sort of wood for the carrier, the desired logo to be milled and the individual mixture of the dietary supplements to be filled into the plastic capsule, the information to produce the product is transferred to the on-product DOM of an unmachined wooden carrier by a read/ write device.

In a first step, the production module of partner company one performs the machining of the wooden block. By reading out the on-product DOM, the milling process is parameterized in order to conduct all relevant steps necessary for this part of production. After the milling has been finished, all relevant information regarding the successful processing of the carrier is transferred to the on-product DOM and available to the following manufacturing steps. Having arrived at the assembly module of partner company two, the plastic capsule is inserted into the wooden carrier by an industrial robot. Before conducting the assembly, the on-product DOM is accessed by the production facility in order to check if the appropriate cavity has been milled correctly and if the carrier is ready for the insertion of the plastic capsule. At the end of this step, again, all information regarding the successful assembly of the two product parts is transferred onto the on-product DOM and now available to the following steps.

In the mobile module of the *SmartFactory*^{KL} the final production step comprising the composition of the ordered dietary supplement mixture is conducted. Inside the module, the pre-produced *smart drug case* is transported on a conveyor belt. On its way to the filling station, on-product DOM information is accessed by the first of the RFID read/ write systems in order to check for the ordered mixture and to check if the former production steps have been executed appropriately. On-product DOM information is directly transferred as a binary code into the PLC of the module parameterizing and starting the process of composing the dietary supplement mixture and filling the pills into the *smart drug case*. That means the production process is only determined by DOM information and signed by low level communication at the sensory level. The supervisory control has only a monitoring and general administrative function, but does not actively influence the order processing. As all order-related information is carried by the product itself, no order management in a centralized backend system needs to be involved. After finishing the filling of the *smart drug case* successfully the second RFID read/ write system updates the on-product DOM with actual information of the conducted process including time stamps indicating beginning and end of production and quality flags indicating the appropriate process flow. After that, the *smart drug case* is sealed with a plastic cap and can be handed over to a logistics provider taking care of its distribution.

VI. TECHNICAL SETUP

In alignment with the in chapter III mentioned requirements a lightweight approach has been chosen in order to make the *drug case* smart. The only instrumentation applied to the product is a comparatively cheap and small passive RFID transponder. The SIEMENS MDS D160 transponder (based on an I-Code SLI chip) operates at 13.56MHz and complies with the well established ISO 15693 vicinity card standard, guaranteeing interoperability with a wide range of state-of-the art read/ write systems in industrial use. Providing 112 byte of configurable storage space, the transponder does not only allow for mere object identification by a URL, but also for storing product- and production-related data directly on-product. As being a part of the SIEMENS Moby D product line, the transponder's properties like read/ write distances or data transmission rates are well specified making it a good solution for the given application.

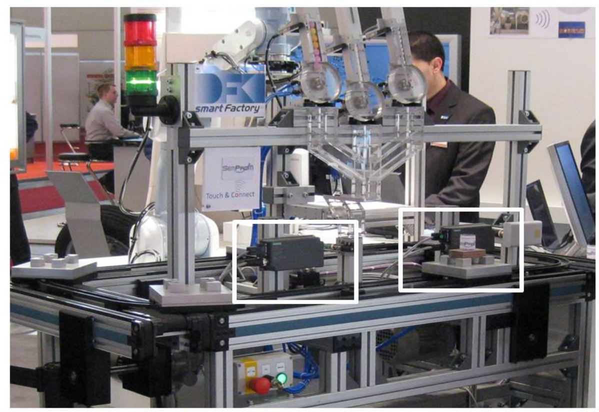

Figure 4. The module of the *SmartFactory*^{KL} with two Moby D read/ write systems and a passing *smart drug case.*

The *SmartFactory*^{KL} module consists of a 0.8m x 1.52m x 1.82m sized hardware prototype equipped with state-of-the-art industrial automation technology. Beside a set of two SIEMENS Moby D SLG D 12 S RFID read/ write systems which are linked to a SIEMENS SIMATIC S7 300 programmable logic controller (PLC), the module is equipped with Bluetooth, GPRS, and WLAN interfaces for external communication. Systems inside the module are connected to the PLC via PROFIBUS, Industrial Ethernet or traditional I/O communication interfaces. The supervisory control of the module is realized by a commercial laptop with SIEMENS STEP7 (for PLC programming) and WIN CC (for process visualization) software installed.

VII. THE IMPLEMENTATION OF THE DRUG CASE DOM

As it has already been the intention to choose a lightweight approach concerning the on-product memory hardware, it is similar with regard to the development of a sleek and slender data structure. Semantic representation of on-product memory content is therefore not to be chosen. Instead, the semantic knowledge to interpret the binary on-product memory content is implicitly contained in the applications interacting with the on-product memory within the different production facilities of the participating partners.

To make good use of the 112 byte of storage space provided and to present product- and production-related information in a simple but reasonable way, all information is arranged in a binary block structure implemented in the storage of the transponder (see Fig. 5).

The header of the on-product memory consists of a 4 byte unix-time stamp indicating the time when the product order has been placed, the ID of the company where the order has been placed, and a continuously increasing order ID (each 1 byte). The combination of company ID and order ID also constitutes the ID referencing the product to the external off-product part of the DOM. Additional product information comprises the product dimensions in millimeters as well as additional handling information for a later use in robot manipulation or logistics (altogether 4 byte).

Information specific to single process steps conducted in the modular production facilities of partner companies are arranged in blocks of similar style. The information relevant to the company responsible for machining the carrier is arranged as follows:

After a unix-time stamp indicating the start of machining (4 byte), the information indicating the sort of wood (1 byte), followed by milling information for top and bottom side of the wooden carrier (3 byte) as well as production flow indicators and quality indicators (6 byte) for a successful production are arranged. The block is closed by a unix-time stamp indicating the end of machining (4 byte).

The same accounts for the arrangement of the information relevant to the assembly process. Between the two unix-time stamps indicating start and end of production (each 4 byte), 3 byte of information on how to conduct the assembly including production flow and success indicators are stored.

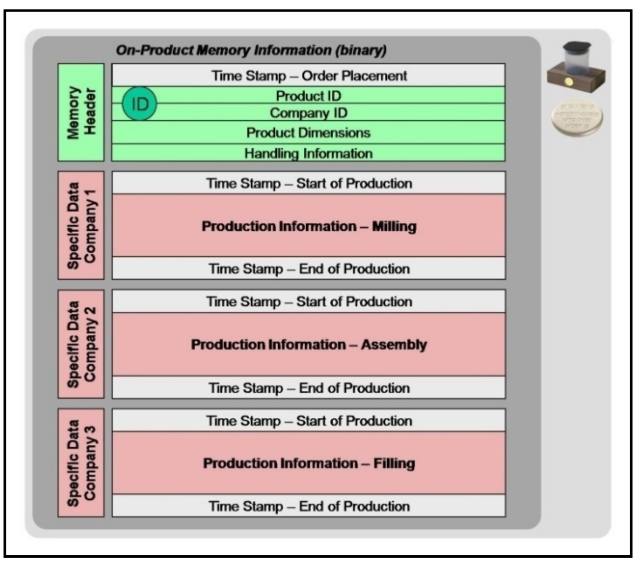

Figure 5. Data structure for the on-product part of the DOM, containing product- and production-related information.

Regarding the information to parameterize the production facility of the *SmartFactory*^{KL}, the information between the two unix-time stamps consists of the chosen dose of the three different dietary supplements (each 1 byte), the correct identification of the capsule (1 byte) and the production flow and success indicators (1 byte).

Altogether, the information to parameterize different production facilities within a circle of partners of the presented scenario comprises sleek 56 bytes which pose no problem to be stored in the chosen on-product memory hardware. Furthermore, the way to arrange product- and production-related information into dedicated blocks allows for the flexible integration of further information resulting from additional product specifications or additional process steps as new versions of the product will come up in the future.

VIII. Benefits of Object Memory Adoption in Factory Processes

Although the presented approach for an on-product memory is comparatively simple in the classical sense, the developed solution proved to work out. Through several test trials and a six day long continuous operation of the prototype system at the 2009 CeBIT[4] fair in Hannover, Germany, the concept of using on-product DOM for parameterization and information exchange between open-loop production processes proved its viability and demonstrated the benefits of DOM adoption in factory processes.

Some of these benefits are more or less apparent, whereas others create added value going far beyond the interaction of a single application with the on-product DOM. In the following, some examples are given on how production and engineering processes will benefit from the use of DOM and how this will change current paradigms in factory planning and operation.

A. Process Monitoring on Item Level

Besides a precise description of a product and its specifications, DOM will enable a very close monitoring of events that happen during a product's fabrication. As demonstrated in the presented scenario, having a look at the entries about the history of a product will allow for a precise drill-down to each single production step, machinery involved, raw materials applied and exact times taken to finalize production. In the future this will enable several kinds of new, value-added services to the company and customers as well. For a company this new degree of transparency will open up the chance to identify untapped potentials for process optimization like the precise identification of bottlenecks. By knowing the reason for a lack in quality from the DOM of a product, the affected lot can be easily identified and replacement of the defective parts can be done at a minimum of cost for the company and to a maximum of convenience to the customer. As a customer's decision to buy a product does incorporate environmental considerations in an increasing extent, it becomes more and more important for a company to reliably document the environmental impact of its products. The reliable determination of a raw material and even the carbon footprint of a product are just one example for a lot more DOM-enabled, value-added services for customers to come in the future.

[4] www.cebit.de

B. Decentralized Process Control

The use of decentralized on-product DOM information to parameterize production facilities is a promising way allowing for more efficient and more flexible factory processes. By storing all production-related information directly on the item to be produced, a production system becomes independent from backend systems and that way far more resistant against disturbances and interruptions in comparison to traditional centralized systems. In the presented scenario for example, the last production step conducted is always recorded in the DOM. In case of interruptions in the production process due to e.g. down-times of a machine, it will not be a problem to keep up with the production of each single product in process, as their individual status is determinable. Referring to [11] this is a highly interesting concept for the production of circuit boards as it helps to avoid rejections. In the future, products knowing about their production will also enable a whole set of new dispatching strategies allowing for a more flexible processing of incoming orders than it is the case today. As the use of on-product information will facilitate parameterization of processes on a very low communication level directly between sensor, PLC and actors, production processes will become more and more independent from supervisory control systems and thus, far more robust towards communication breakdowns. In the case of the implemented hardware prototype, WLAN communication between the supervisory control (installed on a notebook) and the PLC of the *SmartFactory*^{KL} mobile module broke down several times during the CeBIT fair, as the bandwidth in the 2.4GHz band was occupied by too many users. Nevertheless, the core production process of the *smart drug case* could still be maintained hinting at the fact that decentralized control concepts incorporating on-product DOM information are a promising way to increase plant availability and efficiency especially under challenging operating conditions. Furthermore, decentralized control concepts reduce the complexity of control systems in a significant extend and that way, make the production of even the most complex and highest diversified products manageable [11].

C. Cross-Process Information Exchange

As shown in the presented scenario, DOM are a reasonable way to exchange information between various stages of the production. In modular production facilities, even of different stakeholders, on-product DOM can be used to exchange production-related information without the necessity of a communication infrastructure between single modules. Besides the absence of wiring, no hardware communication protocols need to be complied with and no software is needed making the PLCs of different vendors talk to each other, saving huge amounts of costs during planning, installation, and operation of factory systems.

By using on-product memory information of one domain in processes of another domain (e.g. logistics), a higher potential for synergies will be released. For example the physical dimensions of the *smart drug case* stored in its own DOM can be used to parameterize robot handling processes during production or utilized to optimize the packing of a transport box in a logistic distribution process as well.

D. New Degrees of Freedom in Factory Planning and Engineering

Besides the presented advantages DOM will bring for the operation of processes and the exchange for information, several aspects can be identified leading to a more generic benefit going far beyond the saving of wiring and the reduction of complexity. One of those aspects is the fact that DOM and their contribution to a new control paradigm based on decentralized production information will enable true modularity of production facilities for the first time. This means that future factories will not be designed as monolithic “supermachines” anymore but will consist of a multitude of autonomous, self-organizing production modules specialized in providing a certain function or service to a production plant. These production modules will be flexibly exchangeable according to varying product specifications and thereby, enable a production facility to adapt very quickly to changing market demands.

In addition to that, this modularity will allow for new degrees of freedom in planning, setup and initial operation of a plant facility. The following advantages have been experienced during the realization of the hardware prototype system and are deemed to hold also for larger facilities.

As those modules are single entities almost completely independent from each other, they can be engineered in a concurrent way allowing for significantly shorter construction times than this is the case today. As the only communication link between them is the DOM of the product to be produced, the planning and realization of the functionality delivered by the module is completely independent from restrictions regarding the hardware to be used. That means by applying a modular style, the whole engineering process will be reduced in complexity and less time consuming in comparison to established approaches in factory engineering. The same accounts for the ramp-up phase for such a combined system. As all modules involved can be independently pre-tested several times before the initial operation of a whole production line, the time to initiate a facility becomes significantly shorter compared to old fashioned production systems.

Those findings are further supported by experiences made in the *SmartFactory*^{KL} [30], a living lab in which research institutes and partners from industry as well explore the advantages of decentralized control systems in a large production facility of modular style (see Fig. 6).

Figure 6. The modular production facility of the *SmartFactory*^{KL} including process technology modules (left) and discrete production technology modules (right).

Providing a wide variety of benefits for current and future factory processes DOM constitute an excellent basis to prepare a paradigm shift towards the flexible, adaptable and transparent manufacturing of mass-customized products helping the industry to face existing and future market challenges in a highly competitive way.

IX. CHALLENGES TO FACE

As shown in the last chapter, the deployment of DOM has a high potential to upgrade the production and engineering processes regarding the mentioned benefits. However, today these benefits can hardly be achieved because there are several open issues that have to be elaborated before an optimal use of DOM can be realized.

A. On-Board- an Off-Board-Storing

The suggested hybrid approach of the DOM architecture raises the question which data will be stored on-board and which data will be outsourced on an off-board memory. For example, data that contains information needed for the process control has to be stored on the on-board memory. Hence, rules have to be formulated for giving clear instructions how the different kinds of data have to be managed.

B. Restricted On-Board Memory

Today the size of economical acceptable on-board memory is still strongly restricted. The 112 byte memory in the presented scenario is much too small to provide enough space in order to permit a decentralized process control. The costs for lightweight memory with small shape have to decline in future considerably.

C. Protection of Intellectual Property

Since usually there are several stakeholders involved in the value chain of a product, every stakeholder wants to protect his own knowhow. Thus, some data on the DOM has to be deleted before the product goes over to the next company or the access to certain data has to be restricted. Therefore, the question raises which data can be deleted, which has to be stored the whole life cycle of the product, and which security technology can provide a proper handling with secured data.

D. Integration of Technological Changeovers

During its lifecycle a product passes several phases and with it usually several companies. So it can happen that various technologies of DOM are used, for example different types of RFID in the production and logistic domain. Between this technological changeovers there has to happen a capable transition of the data from one technology standard to another.

E. Merging of DOM

Usually a product is built up by the composition of several other products, for example a car. These partial products might have a DOM as well. Thus, there must be a possibility to merge the existing DOM to a superior DOM of the new product. Therefore, it has to be decided which data has to be retained and which can be deleted. Additionally, there are several possibilities of how the data of the composed product can be managed, for example just in a central DOM or decentralized in the old DOM of the product parts.

X. CONCLUSION AND OUTLOOK

Due to shortening life cycles and an increased market demand for mass-customized products, today's industrial production and value chains need to attain a higher flexibility, adaptability and transparency of their processes in order to remain competitive.

As established auto-ID technologies from the "Internet of Things" like barcode and RFID are already closing the gap between the digital and the real world in a variety of applications, so called digital object memories (DOM) are the latest concept to associate digital information items with physical objects.

By organizing object-related information reaching from product specifications to production parameters and sensor readings to additional customer information in a memory like structure, DOM go far beyond present real-life auto-ID applications and are a promising solution to overcome the current dilemma of the production and logistics industry.

The research presented in this paper deals with the use of DOM throughout the life cycle of a product focusing on the production part of the value chain. First the general requirements for a DOM has been discussed and a approach dealing with an hybrid architecture of the DOM has been presented. After this, a scenario of a customized *smart drug case* being processed in different production facilities was described where the concept of DOM has been applied in an example of use.

The developed on-product DOM proved its ability to reliably drive complex, decentralized applications in the modular production process of the *smart drug case* presented at the 2009 CeBIT fair in Hannover, Germany. A explanation concerning the technical setup and the implementation of the data structure was given by means of the mobile module of the *SmartFactory*^{KL}.

Based upon best practices and experiences made during the conducted research, several examples are given on how manufacturing and engineering processes will benefit from the adoption of DOM reaching from optimized monitoring capabilities to a decentralized control of processes to a easier cross-process information exchange up to new degrees of freedom in factory planning and engineering.

In a final step some open issues were mentioned concerning the development of DOM. Thus, the concept of DOM has to be elaborated in the future in order to realize an optimal use of DOM and with it an exploitation of its potential benefits.

Our future research will concentrate upon certain aspects of memory access and design. As the access of each partner company to the memory content is by now realized through proprietary systems, a change in DOM structure will make similar changes in all systems utilizing DOM information necessary. Therefore, one of the goals is to develop a comprehensive middleware containing the semantics and knowledge to interpret DOM content and to provide an interface for unified DOM access also to higher layers of control like enterprise resource planning (ERP) systems.

Furthermore, the current on-product DOM structure is rather driven by existing hardware restrictions. In the future, a more general and open DOM container format will be developed accounting for the incorporation of a broader range of data like sensor readings or user characteristics.

The mentioned aspects are addressed in close cooperation with several partners from the industry who work together in the project *Semantic Product Memory* funded by the German Federal Ministry of Education and Research. Furthermore, the developed concepts will be verified within the experimental production facility of the *SmartFactory*^{KL} in order to test their potential and suitability for real-life applications.

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