Autonomous Control of Intelligent Products in Beginning of Life Processes

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Abstract: Current research into integrating RFID into metal parts has shown the practical feasibility of embedding transponders directly into aluminum during the casting process. This introduces the possibility of augmenting parts with decision making capabilities immediately after casting. Along with concepts from the field of Intelligent Products and models of autonomous control in production such as the Product Variant Corridor and Multi-Agent Systems, the potential for optimizing the Beginning-of-Life phase of the lifecycles of products with such cast RFID are immense. This paper explores these potentials and introduces concepts and methods for the autonomous control of cast-RFID-based Intelligent Products in production and assembly processes.

Keyword : PLM, item-level PLM, closed loop, intelligent products, product variant corridor, embedded RFID, casting, RFID integration

1 Introduction

Intelligent Products are defined as products which are equipped with a unique identifier and are capable of information processing and decision making [1]. These capabilities may be either embedded directly into the product or be facilitated by external IT.

The potential for Intelligent Products early in the product lifecycle is well documented. For example, [3] argues the shift in focus of the manufacturing industry from a supplier-driven market to a customer-driven one, requiring a shortening of product lifecycles, a reduction in time-to-market, an increase in product variety and a fast satisfaction of demand whilst simultaneously maintaining product quality and reducing investment costs. [3, 1 and 4] provide examples of the application of Intelligent Products to production logistics processes.

There are, however, significant barriers which currently prevent a widespread adoption of Intelligent Products to processes early in the lifecycle of products which consist of metal parts. This paper investigates three of these barriers and presents concepts which address how they may be overcome.

First and foremost is the lack of an efficient and robust method of attaching unique identification to metal component parts directly during manufacture. In this context, the paper presents current research towards embedding RFID transponders into metal component parts during the casting process. The second problem is the seamless integration of the information processing components of Intelligent Products into production logistics processes’ IT infrastructure. Here, concepts of hardware abstraction and semantic data integration for Intelligent Products using RFID embedded into castings are discussed. The third challenge is the design of suitable decision algorithms which take into account the requirements towards production logistics flexibility, increased variety and reduction of time-to-market whilst benefitting from the concepts outlined above. This paper proposes the Product Variant Corridor as a suitable approach.

The paper is structured as follows: First, an overview over relevant related work is given, beginning with a look at prior work on applying Intelligent Products to production logistics problems in the beginning of life phase of the product lifecycle. The next section outlines an approach to Intelligent Products comprising the three conceptual components outlined above. The first component deals with effectively embedding RFID into metal parts during casting. The second investigates how such RFID may be integrated into PLM IT-environments whilst the third introduces concepts towards autonomous decision-making in beginning-of-life processes. The paper concludes by illustrating how the three components interact as autonomous, Intelligent Products in a possible beginning-of-life use case.

2 Related Work

2.1 The Beginning-of-Life Phase of Product Lifecycle Management

Product data is needed to design, manufacture, install, operate, maintain and subsequently dismantle products as required both by customers as well as regulation. Product data must be managed as a shared resource for maximum availability to all business functions creating and using it throughout the product’s complete lifecycle [5]. A product lifecycle can be characterized by the following three phases: Beginning-of-Life (BOL), including design and production, Middle-of-Life (MOL), including use and services and End-of-Life (EOL) [6], including disassembly, reuse, refurbishing and disposal.

Research on item-level or closed-loop [6] Product Lifecycle Management generally assumes that the necessity for considering products as individual physical items which create their own data and support demands is generated in the MOL phase. However, the shift in focus of the manufacturing industry to a customer-driven market described by [2] presents a strong argument for item-level lifecycle management of products already in the BOL phase. The aim of managing such item-specific product information is to enable or improve decision making processes in the processes of the product lifecycle. Although there are a number of approaches for the management of item-specific information, none of these currently provide a complete solution in terms of data models, product traceability, data handling including access, transport and request handling capabilities which is readily applicable to real world scenarios.

2.2 Intelligent Products in the Beginning-of-Life Phase

"Intelligent Products" are physical items, which may be transported, processed or used and which comprise the ability to act in an intelligent manner. McFarlane et al. define the Intelligent Product as *"a physical and information based representation of an item [...] which possesses a unique identification, is capable of communicating effectively with its environment, can retain or store data about itself, deploys a language to display its features, production requirements, etc., and is capable of participating in or making decisions relevant to its own destiny."* [1] The degree of intelligence an intelligent product may exhibit varies from simple data processing to complex pro-active behaviour. This is the focus of the definitions in [1] and [7]. Based on these definitions, the level of Intelligence of Intelligent Products can be divided into three categories: *Information Handling*, *Event Notification* and *Decision Making*. This is the first dimension of the Intelligent Product. When each object has its own intelligence, it does not necessary mean that the intelligence is located at the object. In the second dimension, two extremes can be identified*: Intelligence through the Network* and *Intelligence at the object*. Finally, the third dimension of the Intelligent Product is the *aggregation level* of the product intelligence. In general, two levels can be differentiated: *Item level* and *Container level*. The three dimensions of characterization of the Intelligent Product are summarised by [2] in the classification scheme shown in Figure 1.

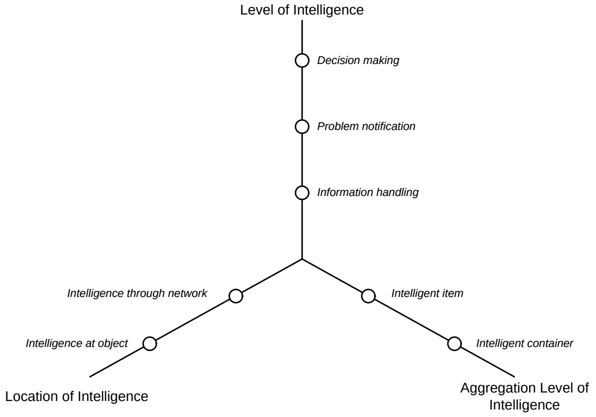

Figure 1: Classification of Intelligent Products according to Meyer, et al. [2]

Intelligent products have successfully been shown to adequately support processes in the BOL phase of the product lifecycle. For example, Ventä describes a number of applications of intelligent products in the BOL phase of different product lifecyles. [3] McFarlane et al. illustrate the use of intelligent products in manufacturing control. [1] Wong et al. look at the application of intelligent products to production, distribution, and warehouse management [4].

2.3 Embedding RFID into Intelligent Products

In order to facilitate Intelligent Products as classified by [2], an approach must be used to embed intelligence into the physical product. In [8], Product Embedded Information Devices (PEIDs) are categorised according to their capabilities with regards to data storage and data processing capabilities (cf. Table 1). In addition to the categories data storage and data processing shared with [9] the devices' ability to integrate sensors as well as their options for network connectivity are used to differentiate different types of PEIDs. The sole common denominator of all types of PEID is however that they contain a global, unique identifier. This fulfils the most basic requirement of an Intelligent Product towards an information device embedded in a physical product.

Type	**Identification**	**Data Storage**	**Sensors**	**Data Processing**	**Connectivity**
Type 0	✓				Passive
Type 1	✓	✓			Passive
Type 2	✓	✓	(✓)	+	Wireless
Type 3	✓	✓	✓	++	Wireless
Type 4	✓	✓	✓	+++	Always

Table 1: Types of Product Embedded Information Devices according to [8]

RFID (Radio Frequency Identification) is currently the most widespread technology which fulfills those requirements. Whilst it has been adopted successfully in many industry sectors, it has yet to successfully be applied to cast metal components. This is mainly due to both the high cost of on-metal transponders and the lack of suitable methods of application, especially in harsh industrial environments.

To provide the basis for autonomous, product-centric decision making in production logistics processes, item-level identification must be guaranteed from the very first steps of production. In the case of metal casting, this means as soon as the product leaves the molding tool. Conventional procedures of marking cast parts do not allow for the volume of data required for unique identification. The most widely used techniques for the identification of cast parts with a comparatively high information content are engraved or laser-cut barcode and data matrix codes (DMC) on the surface of the part. Due to their sensitivity and low robustness these techniques only have a limited applicability [10 and 11].

Castings are currently enhanced with electronic components by using conventional joining technologies such as screwing or bonding. These technologies, however, represent an additional production step, which in turn usually requires more preparation steps like the special pretreatment of a surface or the mechanical treatment of a screw connection.

Current research is investigating how RFID transponders may be embedded into component parts during the casting process. The aim is to reduce manufacturing costs facilitate the individual, item-level identification of the cast parts “from the cradle.” An additional benefit is the protection of the transponder against damage caused by external influences in the manufacturing process, damage or loss, so that tracing the part can be ensured even in a rough production environment.

2.4 Synchronizing the Material and Information Flows of Intelligent Products

Given products automatically and uniquely identifiable via RFID, a means is required to couple that identifier with a so-called “digital counterpart” such as a software agent which provides the “intelligence” as defined by [2] in Figure 1. With regards to passive RFID transponders, a solution should support “intelligence through the network,” that is, information storage and decision making capabilities are held on computing resources external to the product.

A number of concepts and technological approaches exist to efficiently and reliably synchronize the material and information flow of the Intelligent Product. One approach may be found in the ID product identification and information linking concept ID@URI [12]. Here, each product carries the ID of the product, as well as the URI (Uniform Resource Identifier) address of the product’s digital counterpart. ID@URI explicitly facilitates the use of software agents in this context. The ID@URI-based Dialog [13] platform contains two software components. The first is the product agent which manages product information. The second component is used e.g. for updating the location of shipments passing at checkpoints or for querying or updating product information in general.

The Electronic Product Code (EPC) [14] is a scheme for the universal identification of physical objects. EPCIS (Electronic Product Code Information Services) is a standard that defines interfaces for sharing data among stakeholders on the basis of EPC [15]. It allows real-time visibility of the movement, location and disposition of assets, goods and services [16]. The function of the Object Name Service (ONS) is to resolve the EPC into URLs, which may point to a Web Service or other information resource [17]. The EPCglobal Architecture Framework does not explicitly address digital counterparts or software agents. However, it enjoys widespread industry uptake in as a standard approach to providing item-level data visibility and integration throughout logistics processes.

2.5 Integrating Intelligent Products into the BOL IT Landscape

In addition to linking the physical products to their digital counterparts, the diversity of systems involved in complex, autonomous logistics processes defines challenging requirements towards an approach to integrating Intelligent Products into the wider system landscape. The variety of different applications, data sources, exchange formats and transport protocols demand a high level of flexibility and scalability.

Here, different approaches are proposed in literature which are compatible with the approaches to synchronizing the material and information flows as described in the previous section. Most rely on approaches to semantic data integration. The main concepts constituting the architecture of such approaches are mediators [18 and 19]. In this approach, both syntactic and semantic descriptions of the data to be integrated are applied. The semantic mediator is capable of extracting knowledge regarding the data structures of the underlying data sources and subsequently transforming, decomposing and recomposing data requests according to that knowledge. The mediator relies on semantic descriptions of the data sources. In the case of autonomous logistics processes, this implies a wholly semantic modeling of the relevant logistics information and data across the distributed, heterogeneous sources, for which a number of approaches, such as ontologies, may be chosen.

The quality of any semantic approach to data integration is highly dependant on the ontologies upon which they are based. A number of relevant ontologies exist in the field of Product Lifecycle Management, such as the PROMISE Semantic Object Model [20 and 21], which considers descriptions of product structures, properties and conditions, lifecycle phases, events, resources and activities as well as field data, and forms the basis for the PROMISE Messaging Interface PMI [8]. Other examples are discussed in [22, 23 and 24]. Regardless of the top-level ontology chosen for a semantic approach to data integration, the mediator concept is in essence flexible enough even to mediate between alternatives.

2.6 Decision Methodologies in the Beginning-of-Life Phase

The logistics performance of current production systems is limited due to unused flexibility potentials. System inherent flexibilities such as loose coupling of customer orders and parts, or flexible manufacturing process sequencing are not or to only very little extent taken into consideration by today’s production planning and control systems. A new approach to unlock so far not used flexibility potentials is the implementation of autonomous logistics processes [25]. Autonomous logistics processes allow single parts to decide about their own manufacturing process. For a typical job-shop manufacturing scenario, the idea of an autonomous product means, that a part has the capability to route itself through the production process. That includes decisions about the next production process step and the respective work station. Furthermore the part takes into consideration the available product variants and the placed customer orders. These decision alternatives are especially available for product structures with many variants, as one component of a product can become part of many different final products variants for different customers. Which final product variant is favorable depends on the current demand and production situation.

The concept of continuous and participative factory planning for multiple-variants series production offers a method for flexible process planning [26 and 27]. However, the characteristics of autonomous control in the way of decentralized decision making are not included. Another approach generates and evaluates alternative manufacturing sequences according to technologically and economically criteria to find the best manufacturing process in parallel to the product design [28]. However, a sequence change during the manufacturing process is not possible and an autonomous allocation of production and customer order is not integrated, yet. Current approaches do not cover autonomous logistic processes. Especially the option of amending the product variant, with a revised allocation of product and order during the production and assembly process and their impact on the logistical achievement has not been investigated, yet.

3 Methodology

The following sections outline proposed approaches to embedding RFID transponders into metal component parts during the casting process, seamlessly integrating the information and material flows of the component parts and designing suitable decision algorithms which take into account the requirements towards production logistics flexibility, increased variety and reduction of time-to-market. In combination, they propose a concept for the autonomous control of metal component parts in beginning of life processes.

3.1 Cast RFID

The major challenge to the in-process embedding technology is to shelter the sensitive RFID transponder from the high temperature of molten metal and compression load resulting during the pressure die-cast process. Furthermore, the electronic component has to be fixed in position in the casting mold, useable for a large-scale series production. For developing a technology to cast-in transponders for PLM applications some general, fundamental aspects need to be taken into consideration: the positioning of the RFID inside the casting for function properly, a suitable kind of RFID transponder for the intention, the protection of the electronic component against high temperatures of the melt and the positioning of the embedding component in place and fixing inside the casting mold to resist high casting rates and pressures during redensification. The following contribution illustrates the development stage for the in-process embedding of an RFID transponder.

A suitable RFID transponder to cast into the sample casting “RFID rear light” is a glass transponder ‘Sokymat SID153 Hitag S 2048 bit (cf. Figure 2). Its compact construction (2.12 mm of diameter and 12 mm length) is suitable for being embedded into thin walled casting structures. It operates in the low frequency band at 125 kHz (±6 kHz) to minimize disturbances by the metallic environment. Its inductor is wrapped around a ferrite core to improve performance in metallic environments. The peak temperature of the transponder is +120 °C for max. 100 h storage or max. +85 °C for operational use.

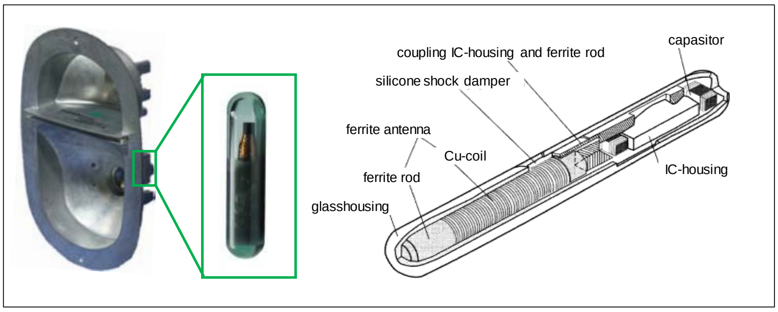

Figure 2: RFID cast part with integrated RFID transponder (left) and design of a glass transponder (right)

An insulation layer can be designed to cover the RFID transponder and to protect it during the die-casting process. Apart from insulation, the main function of thermal protection it can be used for positioning and fixing of the functional component inside the molding tool during the die casting process. Due to these functions the insulation material not only needs to resist the molten metal but also has to provide a mechanical protection for the transponder. On the one hand it has to resist high pressures during redensification caused by the die casting process. On the other hand it needs to hold the functional component inside the molding tool in a fixed position. Furthermore the encapsulation must have good dielectric properties so that the RFID based communication between reader and embedded transponder surrounded by metal can be ensured. Figure 3for thermal-mechanical protection as well as positioning and as dielectric using the example of an automobile rear light.

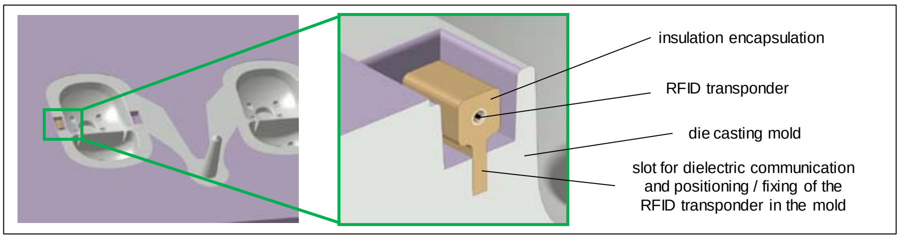

Figure 3: Positioning and Fixing the RFID Transponder with Insulation in the Die Casting Mold

For the experimental work a die-cast unit ‘FRECH DAW 315’ with a closing force of 3150 kN was used (cf. Figure 4). As molten metal a zinc alloy type ZL0410 was teemed by 420° C. The temperature of ejector die and cover was set to 250° C. The encapsulated RFID transponder was plugged into the casting tool manually and automatically ejected with the casting due to positive fitting inside the part afterwards. The metal weight of one reflector (without gate) is 325 g. After ejection the castings were cooled down by water as well as by air at room temperature. Indeed, the zinc alloy used in this experiment has a clearly lower processing temperature with a difference of 290° K in comparison to molten aluminum (approx. 710° C). With a wall thickness of approx. 1 mm and the resulting volume it is comparable to aluminum concerning the heat capacity for that a comparable heat energy having impact on the electronics. This comparison was confirmed by comparative numerical calculations.

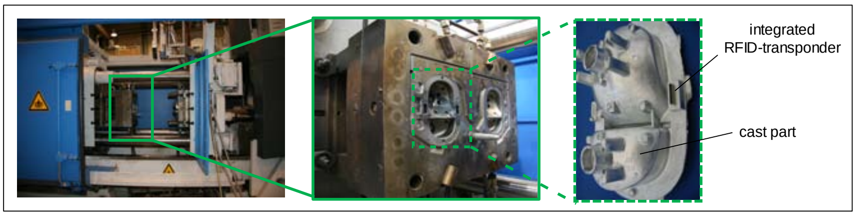

Figure 4: Die-cast unit FRECH DAW 315 (left), die casting mold (center) and final cast part with integrated RFID transponder (right)

3.2 Data Integration

The following describes a concept for the integration of the digital counterparts of Intelligent Products into the IT landscape of production logistics processes. It takes into account the particular constraints dictated by the type of transponder used in the casting process described above in section 3.1.

In the design of RFID-based architectures, it is good practice to abstract from the hardware layer. This guarantees the future scalability of the entire production system along with flexibility towards the underlying RFID reader hardware. The most practical approach to facilitating hardware abstraction is generally to apply middleware standards such as those proposed by EPCglobal. However, the RFID transponders and corresponding readers chosen on the basis of the cast RFID research as currently not EPC compliant. Consequently, an alternative hardware abstraction layer was developed which is capable of interfacing with arbitrary reader devices within the context of production logistics.

In order to allow for future EPCglobal Framework Architecture compliance, the hardware abstraction layer exposes the hardware abstraction interface defined in the Reader HAL (Reader Hardware Abstraction Layer) of the FOSSTRAK project (Free and Open Source Software for Track and Trace[1]).

For the integration of the digital counterpart with the overall IT landscape, a semantic mediator is proposed. It uses the Web Ontology Language (OWL-DL) [29] for the specification of the ontology which describes the individual data sources. OWL-DL was chosen for three reasons: first of all, it is used in the multi-agent system [30 and 31] for the description of the domain of autonomous controlled logistics. Secondly, it was judged to be adequately expressive to cover the semantic description of the data structures of the product lifecycle as exemplified by [20] and the overarching concepts of autonomous logistics processes. Finally, a number of Java libraries and reasoners are readily available for OWL-DL, which was expected to significantly accelerate the development of a prototypical implementation. The query language “SPARQL” [32] is used as the query language at the query interface of the system. It was specifically developed for querying ontologies and thus provides an adequate basis for queries to the semantic mediator. To extend the functionality to support bidirectional queries, the “SPARQL Update” [33] language was used to extend the SPARQL query language. This allows for the editing of ontologies with a similar syntax to SPARQL.

The wrappers query data from the respective data sources and transform it via an internal format in order to enable the processing of data from heterogeneous data sources and formats. The transformation is carried out within the wrappers and is transparent to the actual mediator component. This allows for a complete abstraction from the data sources. Transformation in the wrappers is rule-based and described and implemented using to the business rule management system “Drools” [34] (Drools - Business Logic Integration Platform). The use of Drools offers the possibility to react more quickly and flexibly to modifications to individual data sources. Should a change need to be made, only the rule files need to be updated. Modifications to the source code of the wrappers with subsequent recompilation and deployment can be avoided in this way.

3.3 The Product Variant Corridor as a Decision Methodology for Intelligent Products in Manufacturing and Assembly

The underlying concept of applying Intelligent Products to production logistics processes (manufacturing and assembly processes) is for a product to decide about its next production step. These decisions require different constraints like customer orders or missing parts to be taken into account. An adequate decision method has to consider both, logistics criteria like throughput time as well as technological criteria such as tools machine combinations.

The process of decision making can be divided in five sub processes, namely problem description, definition of target system, generation of decision alternatives, evaluation of decision alternatives according to target system, and execution of the decision alternative with the best target contribution [35]. In the case of autonomous decision-making in manufacturing, the problem in question is how to decide about the next production

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[1] FOSSTRAK homepage http://fosstrak.org

process step. While some of targets in production logistics support each other (low work-in-process and short lead-time), others are contradictory (work-in-process, high capacity utilization). In addition, as mentioned before also technological criteria are taken into account for decision-making. Especially for cases when different machines are available to perform the same operation it is possible to take for example the tool abrasion of the different machines into account or different manufacturing technologies. Different tool conditions or manufacturing technologies will lead to different surface conditions, which are related to the quality standard produced. As different customers might have individual quality requirements, this criterion is part of the target system of the Intelligent Product. The different targets are combined and weighted in the target system in the Intelligent Product. The weighting can to be derived from the company's strategic positioning.

The process of decision alternative generation plays a crucial role in the context of autonomous control, as the Intelligent Product has to gather the required information from its environment. In order to generate decision alternatives the Intelligent Product has to know the different possible production processes and the resulting final product variants. Furthermore, it has to know the accessible machines for the different available production steps. For the evaluation of the different decision alternatives, the product has to be able to collect information about the current situation at the available machines (e.g. machine breakdowns, work-in-process level in front of machine). In order to avoid on stock production and to react to market dynamics, the product has to know the current demand situation as well. To execute the selected decision alternative the product has to communicate the decision to the material flow system, which then organizes the necessary processes.

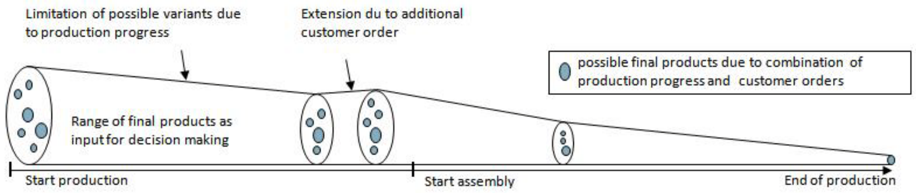

Figure 5: Product Variant Corridor

All the different decision alternatives of the Intelligent Product can be displayed in a corridor shown in **Figure 5**. This corridor expresses which product types for a given production stage and a given number of possible customer orders are generally feasible respectively reasonable to be produced. The corridor narrows down or in the case of new emerging customer order expands again. Only after a customer decoupling point, which requires the specification for an individual customer, the potential of autonomous control in the sense of a dynamic product-order allocation is exhausted. Hence, the corridor allows logistic objects to choose among different product types, as long as it is possible from the product structure view.

A simulation model has been developed to investigate different autonomous control methods based on a framework for manufacturing flexibility [25]. A feature graph has been developed to display all decision alternatives of a part for each manufacturing step [36]. The nodes in the graph represent features. A feature is a property that can be added to a product (mounting a device, painting, etc.). Furthermore, since the result of the production process is not predetermined anymore, it is necessary to detect possible outcomes (variants) for a product during its production process in real-time. To do so, an algorithm has been developed which determines possible final products instantaneously for each production step.

4 Results

Applying the three concepts outlined above in combination results in an Intelligent Product with the characteristics according to Meyer, et al. [2] as shown in **Figure 6**. Due to the breakthrough in embedding RFID directly into metal parts during the casting process, intelligence may be applied to physical products on the *item level* beginning immediately with their creation. The location of intelligence is outside of the physical product due to the current restrictions in the casting of RFID into metal parts. The combination of a hardware abstraction layer compatible with the FOSSTRAK HAL along with the standards proposed by the EPCglobal Framework facilitates the link between the RFID embedded in the physical product and the intelligence located in the network. Consequently, the combined Intelligent Product displays *intelligence through the network*.

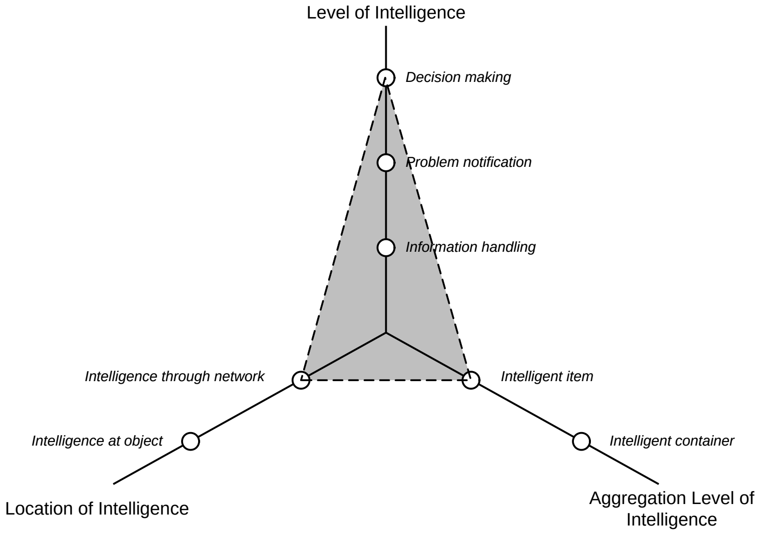

Figure 6: Characteristics of the Intelligent Product according to Meyer, et al. [2]

That intelligence is realized by as digital counterparts of the physical products in a multi-agent system external to the physical product. These digital counterparts autonomously steer the physical products through the production logistics processes using the Product Variant Corridor as their decision algorithm. The digital counterparts have seamless access to relevant data sources in the production logistics IT environment by way of the semantic mediator. Thus, the level of intelligence of the combined Intelligent Product is *decision making* according to Meyer, et al.


Figure 7: Die-cast rear light with embedded RFID

The principles of the described Intelligent Product have been validated in via experiments in different use cases. The process of casting RFID has successfully been developed and applied to die casting automobile rear light parts. A combination of in-process embedded RFID, hardware abstraction and agent-based Product Variant Corridor has been explored using a prototypical demonstrator exemplifying the autonomous manufacture and assembly of the automobile rear lights (cf. Figure 7). A reference architecture combining the semantic mediator with agent-based digital counterparts via EPC Information Services has been developed and applied.

5 Conclusions and Discussion

The concepts and technologies discussed in this paper show a possible approach to implementing Intelligent Products in the BOL phase of die-cast metal products. They exemplify the technology required to provide unique identification of metal parts immediately upon their creation, approaches of linking the physical metal parts with their digital counterparts in the network, a proposed decision algorithm to facilitate their autonomous control along with a semantic data integration approach to provide them with access to relevant data.

With regards to the in-process embedding of RFID into castings, future work will investigate the enhancement of castings for autonomous routing of castings through intralogistic processes of materials handling. With support by autonomous routing protocols and decentralized decision making due to the casting, prospects for a self-adapting of the material flow to actual production situations. The vision of autonomous logistics should give castings the ability to adapt themselves to the actual production situation and to react to troubles within the process by using autonomous methods. Only an identification technology that offers unique identification of a product right by its emergence and the ability to add and save information throughout the production cycle can turn a common data bus between working stations and central control system down. This is a precondition for the development of a local and autonomous production control Work is currently ongoing regarding the data integration concepts following two tracks. On the one hand, research is being carried out close to the hardware level on how to seamlessly integrate sensors and sensor networks into a more generic hardware abstraction layer for Intelligent Products. On the other hand, a semantic service layer including service discovery functionality is being explored on top of the semantic mediator, facilitating a more seamless integration with autonomous, digital counterparts such as software agents and existing IT systems.

Concerning the Product Variant Corridor, ongoing research focuses on assessing different decision strategies. Therefore a scenario generator has been developed, which creates manufacturing scenarios and allows varying the different types of manufacturing flexibility. Furthermore, the implementation of autonomous logistics processes in production encompasses restructuring of common production planning and control methods as processes of the planning level will be shifted to the control level. Implementing autonomous control into production processes requires certain degrees of freedom. Therefore a new approach to order release and capacity planning will be developed, taking into account the implementation of autonomous processes in production planning and control. This will also include concepts of adoptable production capacity. For manufacturing processes this will be achieved by implementing autonomously capacity regulating work systems and for assembly processes autonomous processes for manpower planning will be developed.

With regards to the combination of these concepts as the basis for an autonomous, Intelligent Product, further research will be directed towards identifying the potentials of the proposed concepts for other processing throughout the entire product lifecycle.

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