Dedicated to

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1 Introduction

When the term “Industrie 4.0” was coined in Germany in 2013, the ongoing trend of digitalization was brought to the wider public consciousness. A study published by acatech [1] presents the vision that, in simple terms, can be understood as such: The most important aspect of digitalized production is the cooperation between the components in a plant or configuration and not – as was previously thought – the mere exchange of data between components. Ideally, the elements that should cooperate with each other should be able to make their own way in the production line, i.e. the product to be created should be able to influence its own production. This approach promises more flexibility in the production process, allowing for customized mass production (lot size 1) that can compete with the costs of general mass production today. This approach helps streamline technological processes such as:

- automated and semi-automated engineering
- significantly improved interoperability
- ability of components to provide information
- temporal traceability and localization of relevant components
- more flexible production processes
- significantly improved maintenance
- greater transparency
- lower costs
- quicker set-up times with options for optimizing during the lifetime of a plant

The likelihood that many of these goals can be reached is high because Industrie 4.0 can be viewed as a part of the extensive work on IoTS[1] , which, as a collective term, stands for the digitalization of the world we live in.

In its essence, Industrie 4.0 is the comprehensive digital reflection of the physical world in the information world. To better understand what this means, typical industry requirements, the current state of technology and current technical trends are described in this book. For the sake of ease, the term Industrie 4.0 is mostly abbreviated to I4.0.

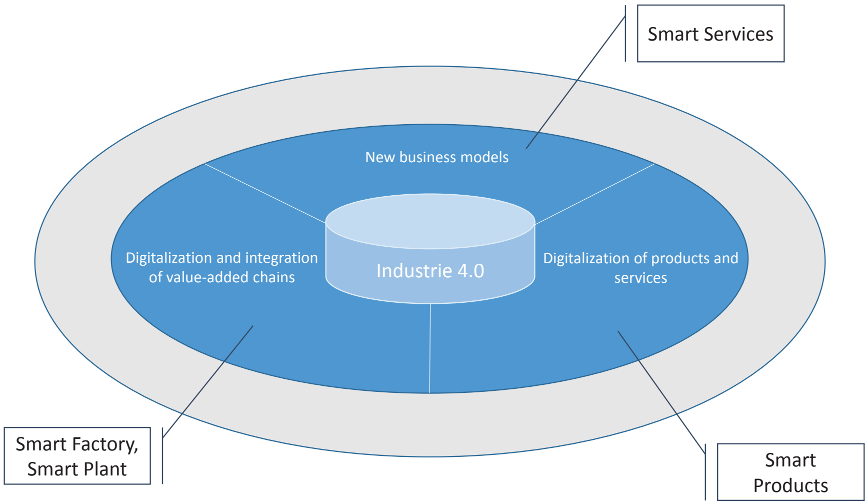
“Big data”, the analysis of data in the information world, is an example of one application of Industrie 4.0 that is not addressed in this book.

1 IoTS stands for “internet of things and services”.

2 Positioning Industrie 4.0

Industrie 4.0 is understood to be a subcategory of the internet of things and services (IoTS). As Picture 1 shows, the basic technology being developed is intended to cover the following three core areas in all sectors.

– Smart Factory[2], Smart Plant
– Smart Products
– Smart Services

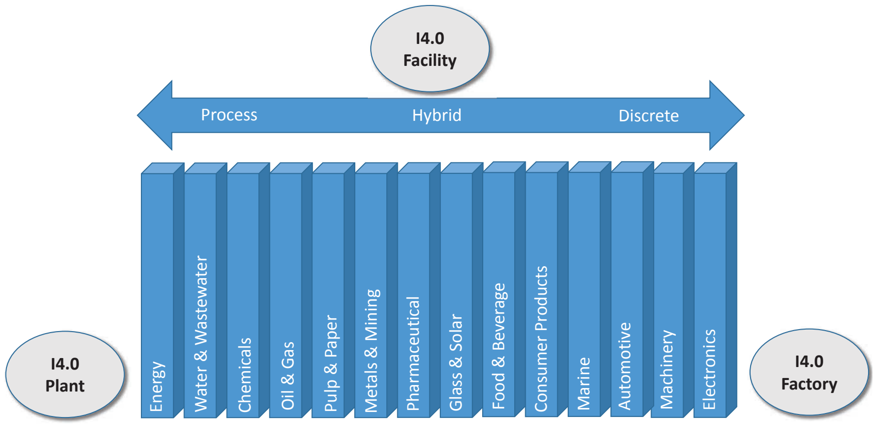


Source: ZVEI and PwC (PricewaterhouseCoopers GmbH)

Picture 1: Work framework for Industrie 4.0

This applies to the entire industrial sector, covering around 15 different branches, as it can be seen in Picture 2. Unlike the consumer market, the manufacturers of automated technical components have always faced the challenge of cross-sectoral implementation in difficult environmental conditions. Without cross-sectoral systems, acceptable production costs could not be achieved for sufficient piece numbers of these components. The customer wants maximum quality at consumer prices.

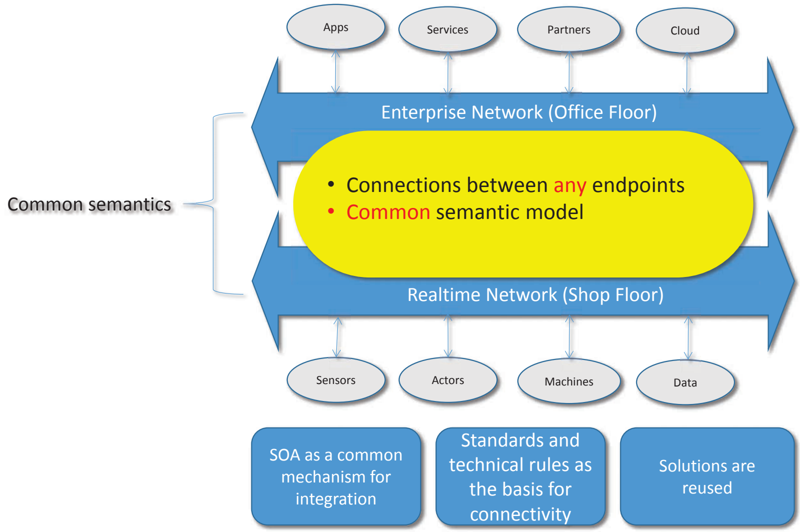
2 “Smart factory” essentially refers to production technology and “smart plant” refers to process technology. Combinations of both amount to hybrid application situations.



Source: based on material from Siemens

Picture 2: Industrie 4.0 needs to meet the conditions of approx. 15 different branches

Company structures generally have at least two levels: the “office floor”, where administration and organizational tasks dominate; and the “shop floor”, where products are manufactured. Even today, these two levels still operate separately in most cases. This applies to the planning and carrying out of processes, management and responsibilities leading to different IT data models being present on both levels. The result is a lack of data integration between the two levels. Picture 3 shows both levels connected with the need for the (largely) barrier-free integration of information (connections to selected endpoints and a common semantic model). This is only possible if the same data model for exchanging information (this involves more than the mere transfer of data) is used on both levels. Large companies can prescribe this sort of data model to their sub-contractors; small companies cannot. Sub-contractors who have many different customers suffer under the various data models they are obliged to use. Because of this, one of the main goals of Industrie 4.0 is to specify a generally valid data model that all business partners can use, thus enabling the elimination of inconvenient, cost-intensive and error-prone parallel structures, and the transfer processes they necessitate. Only with the use of common semantics will the data integration between the two levels become possible. A reference architecture model that can fulfill these requirements is therefore needed.



Source: based on ZVEI

Picture 3: Common semantics facilitates data integration between the shop and office floors.

3 Requirements for a reference architecture model for Industrie 4.0

This chapter explores the fundamental issues that should be addressed by a reference architecture model for Industrie 4.0. To illustrate this, a production line scenario is used to help define the elements addressed in following chapters.

3.1 Characteristics of a reference architecture model

According to the generally accepted [2] modelling theory [3], a model has the following elements:

- a purpose,
- a reference to an original and
- defined properties abstracted from the original.

Examples of digital models and model perspectives are:

- data models
- state models
- interface models
- process models
- structure models (physical or logical)

Traditional engineering models with equations cannot be applied to information technology. Industrie 4.0 uses discrete models.

According to Wikipedia and other sources, a reference architecture in information technology is a reference model for a class of architectures. The reference architecture can be viewed as a template model, i.e. as the ideal typical model for the class of architectures to be modelled [4]. With the reference architecture model, Industrie 4.0 does not specify "the" architecture per se but rather a framework with minimum requirements. This includes the stipulation of terms and a methodology with set rules regarding the following:

- descriptions of the physical world for the purposes of reflection in the information world;
- a reflection of the physical world in the information world;
- a representation of the physical world in the information world;
- the identification of components;
- the connection of components (orchestration);

– the cooperation among components (choreography);
– a network structure and data format for the exchange of information between components;
– minimum requirements for implementation;
– and much more.

The goal of Industrie 4.0 is the creation of a methodology for the coordinated transfer of all relevant information from the physical world to the information (digital) world for the purpose of comprehensive computer-aided automation. In this book, this is described using the term "reflection". Reflection describes the process of creating a virtual depiction of the reality in form of data in the information world. These data are structured according to uniform rules, so that a homogeneous description can be guaranteed. A standard information model needs to be specified for the information world of Industrie 4.0[3], in which the data play a pivotal role. The specifications of the reference architecture model must be adhered to in all solutions (applications) if they are to be Industrie 4.0-compliant. This will ensure the basic transferability of information and the interconnectivity of IT systems. The following chapters are dedicated to this methodology.

3.2 General requirements within Industrie 4.0

Certain framework conditions of Industrie 4.0 dictate that the requirements for products here are much stricter than in the consumer world. These are some of the requirements [5]:

– IT security and data protection
– functional safety
– reliability
– scalable integrability
– interoperability
– transparent connectivity
– integrated, reliable data management
– extended data analysis
– robust controls
– ad hoc capabilities and plug-and-play

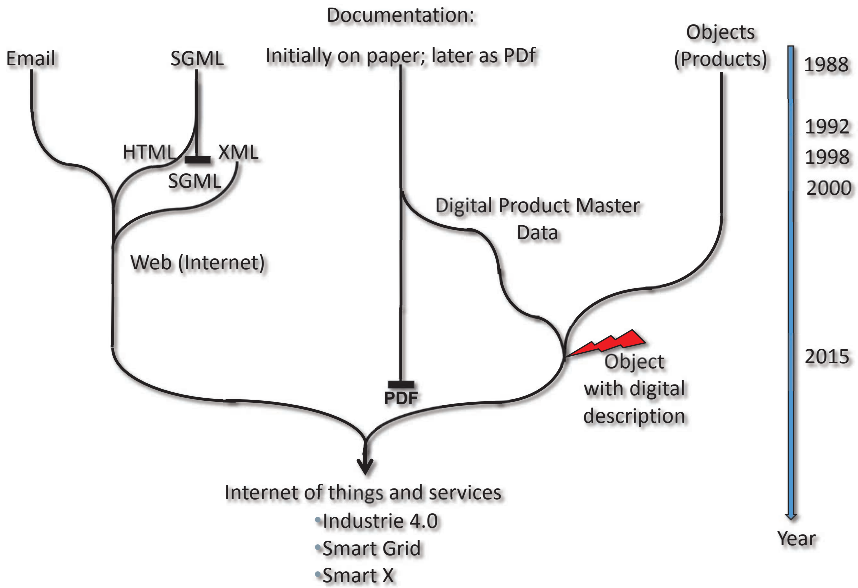
3 Industrie 4.0, IEC CDD and eCl@ss use IEC 61360 and/or ISO 13584-42

The security requirements are particularly strict. In Industrie 4.0 they are expressed by the phrase “security-by-design” (SbD) as without sufficient security, IoTS in its entirety, and by default therefore Industrie 4.0, would not even be possible.

3.3 The current state of technology

Picture 4 shows the development of internet description technologies and the digitalization of product information over the last 20 years. On the left, the development of the internet is shown in terms of the development of markup languages already introduced in 1986. The first noteworthy markup language was SGML (Standard Generalized Markup Language), standardized as ISO 8879:1986. SGML made it possible for a limited group of users to describe specific items of information. But the breakthrough came with HTML and XML, which we know so well today. While the continuous development of the provision and use of information was noticeable in the IT world, product documentation, including that which dealt with digital products, was only available in paper form until the turn of the millennium and thereafter only in PDF form. In neither case are machines capable of evaluating the content of these documents. The birth of electronic business hype at the turn of the millennium witnessed an increase in buyers demanding data sets from their suppliers, including properties such as price, discount and availability. Since then, the German association eCl@ss e. V has been classifying products for more than 30 branches and attributing properties to them [16]. In 2004, the User Association of Automation Technology in Process Industries (NAMUR) started specifying properties for process engineering, through the consortium PROLIST International e. V. The contents of this consortium flowed almost exclusively into eCl@ss and were standardized in the IEC 61987 series of standards.

In Picture 4, the red lightning symbol shows the critical point at which a product is capable of describing itself. This is the point at which the product is united with its own technical description – until this point they are not connected. The physical world of a technical asset and its description (a data set in the information world) come together here. This means that an asset that is equipped with information about itself is capable of passing on information about its own capabilities. It also means that other assets can request the same information about this asset, such as its capabilities, structure and communication properties (“self-x functionality”).



Picture 4: An asset and its data description come together

The symbiosis of an asset and its machine readable description results in the birth of something fundamentally new. It is a component that has the ability to cooperate with other components that have an identical structure in terms of their information from the information world. The basic component of Industrie 4.0, the so-called I4.0 component, is the result of the symbiosis of the physical world of a technical asset and its machine-processable specification in the information world.

The future scenarios of Industrie 4.0 can be described according to [1], using the aspects described in the example. Requirements are used to describe a scenario in which many of the core functionalities of Industrie 4.0 are to be fulfilled. Sections of particular importance are underlined.

Table 1: Future scenarios for Industrie 4.0 according to acatech [1]

„[…] They are characterized by a new intensity of socio-technological interaction of all actors and resources involved in the production. At the center is a network of autonomous, situationally self-controlling, self-configuring, knowledge-based, sensor-supported and spatially distributed production

resources (production machinery and robots, conveying and storage systems, operating equipment), including their planning and control systems. One core element of this scenario is smart factory. Embedded in intra-company value-added networks, smart factory is characterized by integrated engineering that encompasses not only the production but also the product that is produced. It does this by seamlessly integrating the digital and physical worlds. Smart factory makes it possible for humans to master the increasing complexity of production processes and even makes production attractive, economical and compatible with an urban environment.

Industrie 4.0 gives rise to smart products that are uniquely identifiable and can be located at any time. From the production stage onwards, they possess knowledge about their own manufacturing process. Because of this, smart products in certain industry branches can effectively find their own way to each station in their production process. Furthermore, it can be assured that the finished product is aware of the parameters of its optimal operation and of its operating conditions over its entire lifecycle and thus for all states of wear of the product. All this information is used to optimize a smart factory in terms of logistics, usage and maintenance. The information is also integrated into the operational IT applications.

The future scenarios presented by Industrie 4.0 are able to take into consideration individual customer-specific and product-specific criteria in terms of drafting, configuration, ordering, planning, production, the operation itself and even recycling. Even late-notice changes desired just before or during the production (and possibly during the operation) can be implemented. The production of individual pieces and minimum quantities can therefore become profitable.

The implementation of these future scenarios gives employees the chance to control, regulate and shape the intelligently connected production resources and steps according to the aims of the situation and context. This takes routine tasks out of the hands of the employees, allowing them to concentrate on more creative, value-adding tasks. Thus, they are able to play a decisive role and, most importantly, are responsible for quality assurance. At the same time, flexible working conditions allow employees to better shape their work around their individual needs. […]“

If we summarize the contents of the example, a flexible production line is what is called for, along which all components relevant to the production process autonomously organize themselves on the basis of an incoming order. The intention is that the physical world and the information world are seamlessly integrated. Intelligent products should be clearly identifiable and locatable. They possess information about their production while being manufactured. The finished product possesses a life cycle (vita). Because a manufacturing plant consists of multiple products of this type, the same is true for the plant itself.

Production should be flexible enough that it is possible to manufacture products with a quantity of only one piece while retaining profitability. Humans will be able to turn their hands to creative and value-adding tasks instead of resorting to mundane manual tasks – all while experiencing better working conditions. And even if realizing the requirements described here does not seem possible in its entirety right now, many similar approaches can already be recognized in areas such as 3D printing, for example.

3.4 Scenario: The versatile factory

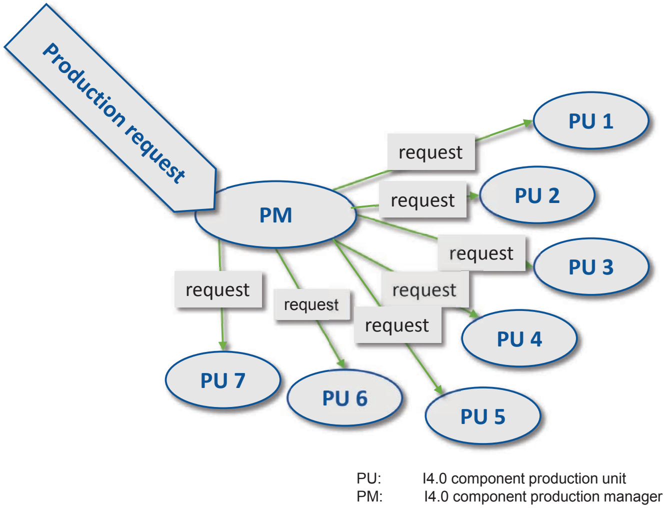
The paper “Fortschreibung der Anwendungsszenarien” (The projection of application scenarios) published by Plattform Industrie 4.0 describes a series of scenarios [6]. One of these scenarios is the versatile factory. It is stated that the application scenario of the versatile factory describes the quick and, under certain circumstances, largely automated alteration of a production line, both with regards to a change in production capacity and capability. “A central notion for the implementation of this is the modular and thus adaptable production within a factory. Intelligent and interoperable modules that can adapt themselves to suit different configurations and standardized interfaces between these modules enable the production process to be quickly and easily adapted to meet new or different market and customer requirements. While the focus of order-driven production is on the flexible use of existing production installations (via intelligent connectivity), this scenario describes the ability of a single factory to adapt by means of (physical) restructuring. This is where modular, order-driven production configurations that are adaptable come into their own: They increase both the general workload of the production and also the deliverability. This changes the requirements placed on individual machines and production modules. Even more important than the great variability of specific production processes is the principle and simple ability to combine individual modules. For this to be achieved, the modules must contain a self-description (self-X capability) so they can quickly and easily be combined or converted into a machine/plant”.

The analysis of this scenario leads us to understand that we are dealing with adaptable production configuration within a factory for the purposes of a change in the production capacity or capability – at short notice. This means that in future there will have to be a combined MES[4]/system integrator functionality, where the system integrator functionality uses the MES information to generate the correct machine configuration, selecting from a pool of machines reserved for this purpose. The MES functionality uses its knowledge of this configuration to control the actual production. In the following, examples of this type of scenario are described in more detail with the aid of schematic diagrams. For the sake of ease, the combined MES/system integrator shall be called the “production manager” (PM) and the individual machines in the machine pool shall be referred to as “production units” (PUs).

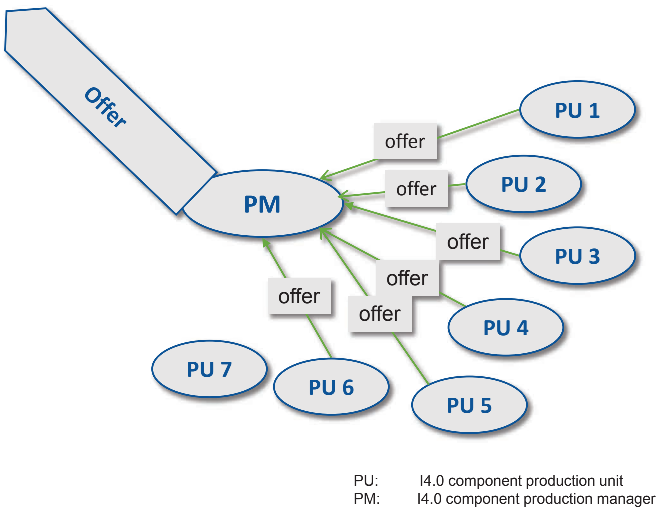
Based on the order in question, the self-configuring production line will generate the optimum configuration of PUs to manufacture a specific product. It will then carry out the automated manufacture of them under direction of the PM. Essentially, this can be seen as the automated generation of cooperative relationships between suitable PUs that are able to describe their own capabilities and subsequently execute functions automatically. The product itself can also influence this process throughout. Picture 5 to Picture 8 illustrate this process.

Picture 5 shows an example of a pool of PUs and one PM. The PM receives the production request and uses I4.0-compliant services to check whether production is possible with the capabilities of the PUs available in the pool. This check includes, among other things, the availability of the PUs and their price for each production step, which allows a price to be generated for the whole order (Picture 6). This forms the basis of the quote for the customer. The part being produced can also affect this process itself, such as if a property forms a substantial reasoning for the price and thus can be changed to reflect a certain price.

4 MES = Manufacturing Execution System (IEC 62264).



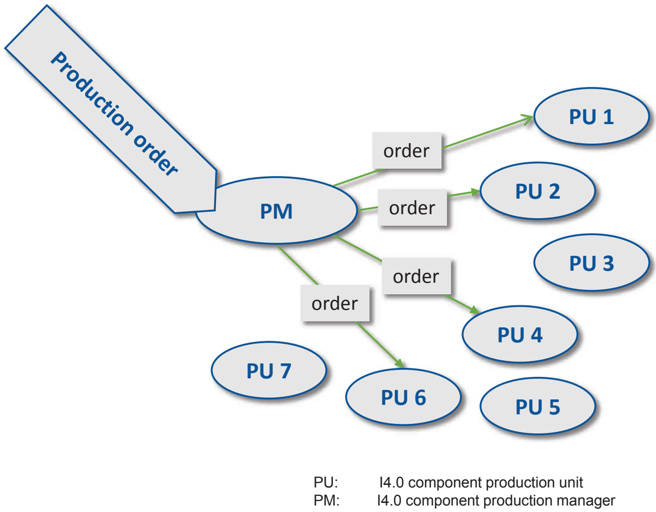
Picture 5: Production request and checking of production resources taking as examples of a production manager (PM) and production units (PUs)



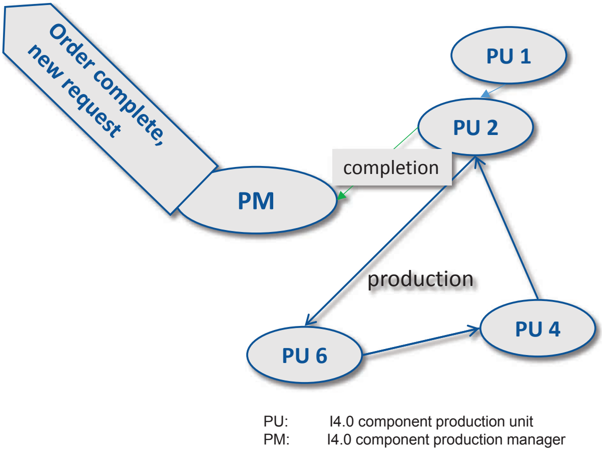
Picture 6: Production offers are returned by the PUs. Not all PUs are required to deliver an offer. In this case, this is PU 7.

After (automatic) agreement with the customer on the framework conditions, the customer provides the order on the basis of the quote provided (Picture 7). The PM then sends an (electronic) order confirmation to the customer and supplies the PUs booked with the relevant tasks. The part being manufactured can even intervene in this process, in certain situations.

Once the PUs have all completed their respective tasks, the PM declares the order finished and is ready for a new production request (Picture 8). With certain designs, the PM can process a new order request while the previous one is still being finished.



Picture 7: A production order is placed



Picture 8: The production process and completion notification

Important elements of this scenario example are:

Initially, the PM can be viewed as an "instance". It takes on a digital request for the manufacture of a product controlled by a human, e.g. a product with a quantity of one. A computer that acts as a customer uses the PM request service. The PM algorithm communicates the required production functions and scours the available PU pool for suitable PUs (production resources) by sending it requests. If it is successful and certain conditions are fulfilled (e.g. PUs are available and the price per production step is right), and if the responsible party from the relevant department has given their approval, the PM sends a digital offer to the customer. If the customer accepts the quote, the PUs organize themselves as a production line, make the product and inform the PM that the order is complete. Finally, the PM triggers the sales processes of the company, which lead to the product being delivered and the invoice being settled.

In order to reach a stage where a collaborative human-machine-machine platform exists, complicated processes must occur. The person involved in this relationship is not only an element of the production line but also oversees the processes.

This results in some technology requirements of Industrie 4.0:

– The request sent to the PM and PUs is service-oriented, which enables the realization of the self-x functionality of all Industrie 4.0 components, among