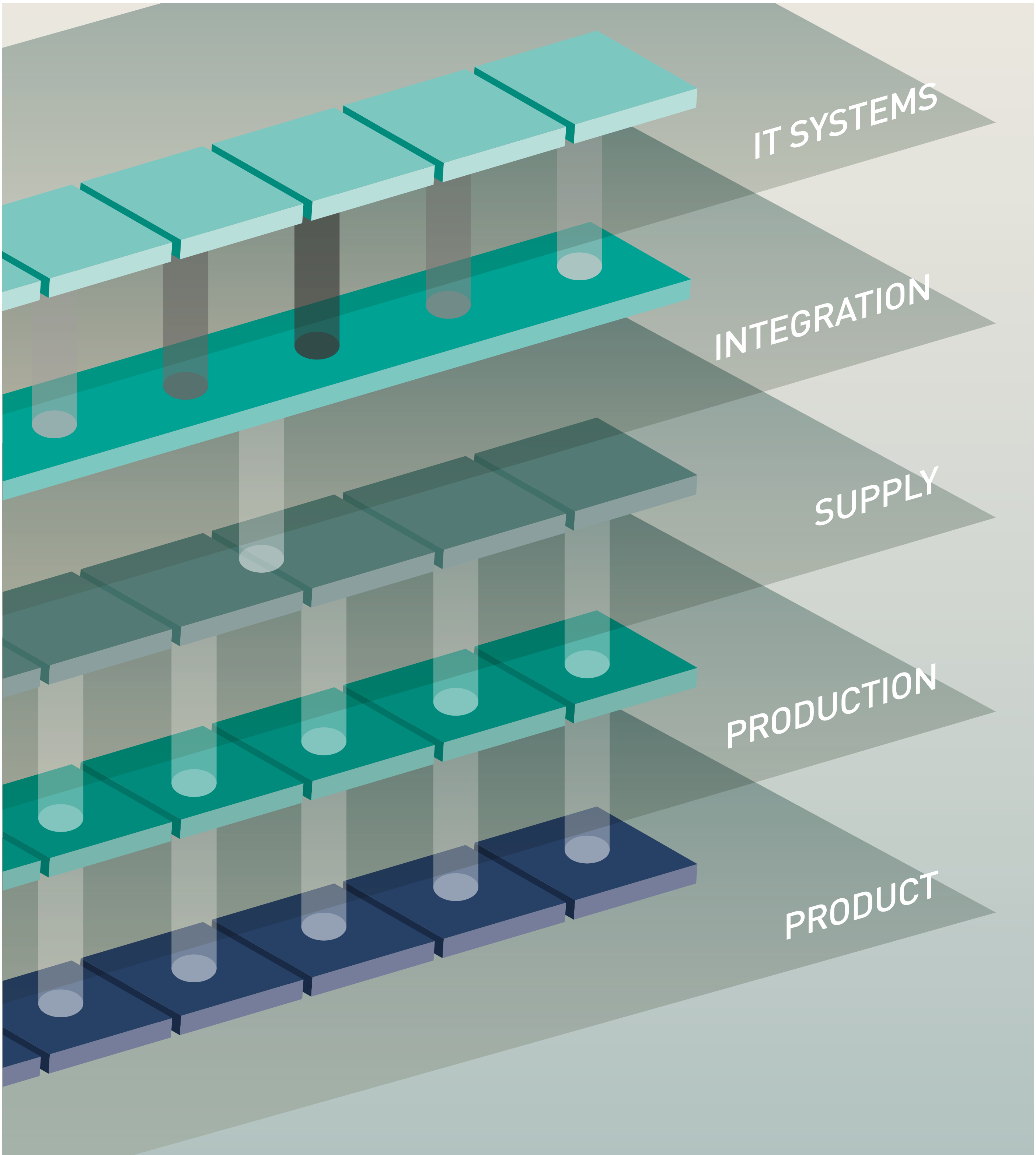

SmartFactory[KL] System Architecture for Industrie 4.0 Production Plants

Whitepaper SF-1.2: 04/2018

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Abstract
The system architecture for the Industrie 4.0 production plant (I4.0 plant) serves as a model technology solution that assists users in making customized products and provides long-term flexibility at discrete, automated assembly production facilities. The system architecture specifies interfaces and describes, from a mechanical, electrical and information systems point of view, an approach to the modularization of I4.0 systems that makes vendor-independent implementation possible. The system architecture enhances the findings of the previous white paper[1] by exploring new areas and expanding on others such as the role of logistics and modularization within the production module. The practical implementation has been successfully tested by ***SmartFactory***KL and its partners.

Keywords
mechatronic transformability; customized mass production;
inter- and intra-company networking; Smart Factory; Industrie 4.0;
modular production

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1 see http://smartfactory.de/wp-content/uploads/2017/08/SF_WhitePaper_1-1_EN.pdf

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1. Introduction

The market trend is towards shorter life cycles and a greater range of variants to include customized products, which leads to new demands on manufacturing for the future. Recent developments show that these megatrends are no longer just visions of the future, but are already relevant today. Using the automotive industry as an example, this trend can be observed in the increasing number of configuration options for cars and the sudden downturn in diesel and upswing in electric motors. This change is confirmed by experience at the Smart-Factory Technology Initiative. These examples show that the production of tomorrow must be versatile enough to adapt to Target criterias that may still be unknown today.

Industrie 4.0 and digitalization are technological approaches to achieve a transformation in production that is of increasing importance. Decentralization of the control logic, from one central system to several, more cost effective, smaller controls can independently manage resources and carry out processes as well as handle the operational and machines' condition data. The decentralization of computing power enables the modularization of production. Consequently, this enables the conversion/retrofitting of the I4.0 plant, as well as shortens the reconfiguration time for new products. Integrated networks using a common language are not only a necessary prerequisite for machine-to-machine communication, but also for the transparency across all production processes and for enabling subsequent expansion of the production plant. Modularization as well as integrated networking require clear specification of the interfaces, without which the plug&produce concept and the future of smart factories cannot be realized[1].

Production environments are complicated systems based on the complex interplay of organization, technology and people. As a result, a holistic approach of the interfaces is required from different domain profiles. Although Industrie 4.0 and digitalization have to be individually tailored to the respective production circumstances and objectives, there are recurring patterns. This system architecture combines these experiences and patterns into recommended actions.

Based on several years of experience in the ***SmartFactory*KL** partner consortium, the following ***SmartFactory*KL** system architecture (Version 2) presents recommended actions for the implementation of a modular and flexible I4.0 plant. It considers the mechanical, information technology and supply-technical aspects of modularization and describes dependencies and building blocks for implementation. In particular, being the further development of an existing white paper (version 1), this version sharpens the boundaries of the elements in the system architecture and widens the role of logistics.

This white paper provides a template for companies developing digitalization strategies and Industrie 4.0 projects. It also helps to understand the technical potential of digitalization in solving future production Target criterias. Section 2 first derives and specifies the Target criterias. Section 3 is devoted to the architecture and the specification of the interfaces. Section 4 describes how the architecture is implemented at the ***SmartFactory*KL** Industrie 4.0 production plant. Section 5 looks ahead to the next steps and future interaction with other concepts.

1 Weyer, S.; Schmitt, S.; Ohmer, M.; Gorecky, D.: Towards Industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems. INCOM, Ottawa, Canada, 2015

2. Target criterias

The ***SmartFactory*****KL** system architecture aims to take future developments into account to accommodate all the Target criterias of an Industrie 4.0 plant. For the future of manufacturing, the following exogenous trends are included in the system architecture.

The increasing market demand for customized products leads to ever smaller batch sizes in production and an even higher variety of variants – even a "lot size 1". Examples of the implementation of customized production can already be found at Adidas[2] or mymuesli[3]. This requires the development of new approaches to material flow controls and rapid adaptation of automated systems.

The trend towards ever-shorter product life cycles only intensifies these Target criterias. The costs of (re-)engineering and re-equipping the plants are becoming increasingly important.

Finally, Industrie 4.0 and digitalization in manufacturing hold the promise of various potentials to make production more efficient. Decreasing hardware costs with smaller components and higher performance make it possible to implement applications today that were not economically feasible just a few years ago.

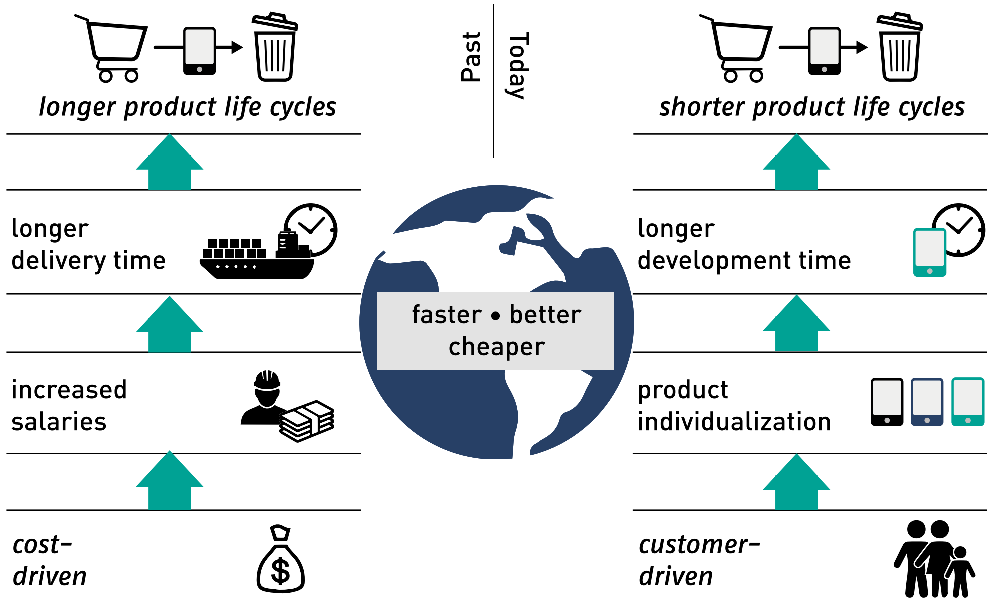


Figure 1:
Trends that influence future production

2 see http://www.adidas.de/personalisieren
3 see https://www.mymuesli.com

Three target criteria that derive from the challenges presented by these three exogenous trends must be met to achieve a comprehensive solution: It is possible to produce more diverse products because of high variability in production. Adapting quickly to shorter life cycles to achieve a higher frequency of new products requires convertible production lines. Finally, increasingly complex production networks will require greater network transparency.

The Target criterias of the system architecture for smart factories derive from these three target criteria. The scope of this white paper focuses on the planning of new plants, so called "green field" plants, in the general common goods area. In the case of the existing vendor-independent Industrie 4.0 production plant at ***SmartFactory*****KL**, a special focus is on modularity and architecture. No discussion of safety and security in the context of the system architecture or their detailed classification in RAMI 4.0 is included in this white paper, as this can be found in other publications by ***Smart-Factory*****KL** [4 5].

Target criteria 1: High production variability

Requirement 1.1: Flexible manufacturing processes

Flexible manufacturing means that not every product undergoes the same processes, respectively, not in the same order. In addition to flexible functionalities, product customization also needs flexible material flows. Among other things, this implies a data transfer between production modules and a flexible logistics link.

Requirement 1.2: Flexible functionalities

Flexible production means that not every product share all production processes or run through all processes in the same sequence. In addition to the flexible functionalities, product customization also requires flexible material flows. This requires, among other things, a transfer of information between the production modules and a flexible connection to logistics.

Target criteria 2: Fast Conversion

Requirement 2.1: Fast retooling (setup) and operation

The shorter life cycles and smaller lot sizes create the need for more retooling operations. However, efficient production also demands a quick conversion of

4 see http://smartfactory.de/wp-content/uploads/2017/11/SF_WhitePaper_2-1_EN-1.pdf
5 see http://smartfactory.de/wp-content/uploads/2018/04/SF_WhitePaper_Safety_3-1_EN_XS-1.pdf

the production lines, simple parameterization of new plant sections, and automated initial setup. This means the previously mentioned need for flexible manufacturing operations must be considered. Another reason for agility in the I4.0 plant is to prepare for the inclusion of future functionalities or scalable expansions that, perhaps, are currently unknown. This agility is possible, for example, through the use of modular components that rely on standardized interfaces. Care must be taken to ensure a practice-oriented design of the interface to enable the simplest possible replacement and integration.

Requirement 2.2 Networking of IT systems

The retooling of the physical plant also has an influence on the IT systems. The connected IT systems are also designed to integrate into the existing environment with the least possible effort. The user should be enabled to arrange higher-level IT systems according to the given demand and to network them with other IT systems and the I4.0 plant at the least possible cost.

Target criteria 3: Transparent Production

Requirement 3.1: Integrated data transfer

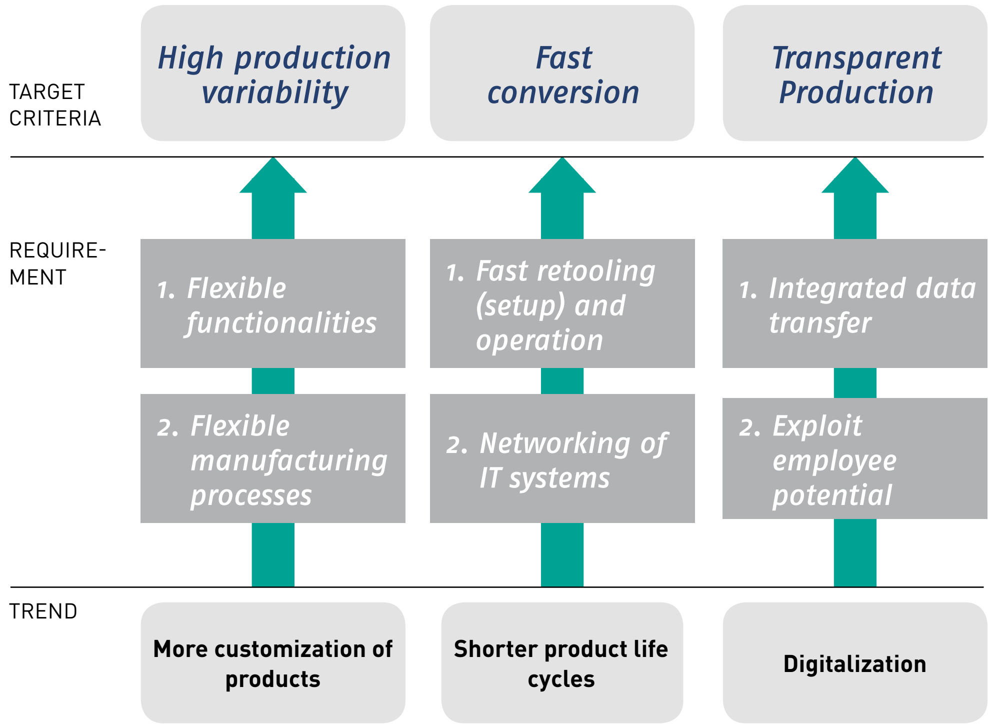
The increasing diversity of variants and the adaptable I4.0 plant increase the complexity of the systems. Goods and information flows are constantly changing and are difficult to predict. To maintain the overview and control, an I4.0 system must enable the transparency of the operations. Only in this way can a quick error analysis and elimination be performed and an optimization achieved. All relevant data – from the production modules to the IT systems must be accessible, preprocessed if required, and made available.

Requirement 3.2: Exploit employee potential

Digitalization and Industrie 4.0 have learned from the CIM era. The paradigm of robot factories devoid of human beings is obsolete. Human workers are an essential, decisive, and central element of any future production. Human strengths like experience, intuition, and flexibility are required. The collaboration between humans, machines, and IT systems in production requires continuous data transfer and processing of information. This is the reason for employees continuing to make decisions in a complex system. At the same time, work in complex production environments is supported and facilitated by assistance systems.

Six requirements emerge from these target criteria that must be taken into account and incorporated into the system architecture when implementing the I4.0 concept. Figure 2 shows an overview of the dependencies between trends, target criteria, and requirements. It shows the basis for the further development of the ***SmartFactory*KL** system architecture discussed in the next section.

Figure 2:
Dependencies between trends, target criteria and requirements



3. Architecture

The system architecture introduced in this section represents the advanced development approach of an I4.0 plant[6]. A special focus is given to the possibility to modularize production modules and IT systems, as well as the role of logistics. Complementing this conceptual section, a practical implementation of the architecture is presented in section 4 using the demonstration environment of the ***SmartFactory***KL.

The system architecture uses the modularization approach to achieve the highest possible flexibility. A module is an abstract term for a self-contained system that independently provides some functionality. Each module is characterized by clearly defined interfaces and a description of the functionalities it can provide. Furthermore, it must specify from which class in the system architecture it is derived. A class refers to a specific part of the system architecture (Figure 4).

As a kind of "black-box" approach, the exact implementation of the function within the module is unknown, only the interface and utilization is given. Modularization enables the "assembly" of an I4.0 plant system (Figure 3) while supporting the requirements for flexible manufacturing functionalities and rapid retooling (Req'ts. 1.1 and 2.1). Complexity is reduced and, similar to the service oriented architectures (SoA), production processes can be orchestrated. The modules are developed as dedicated solutions for dedicated tasks according to the "separation of concerns" approach – as known from computer science studies.

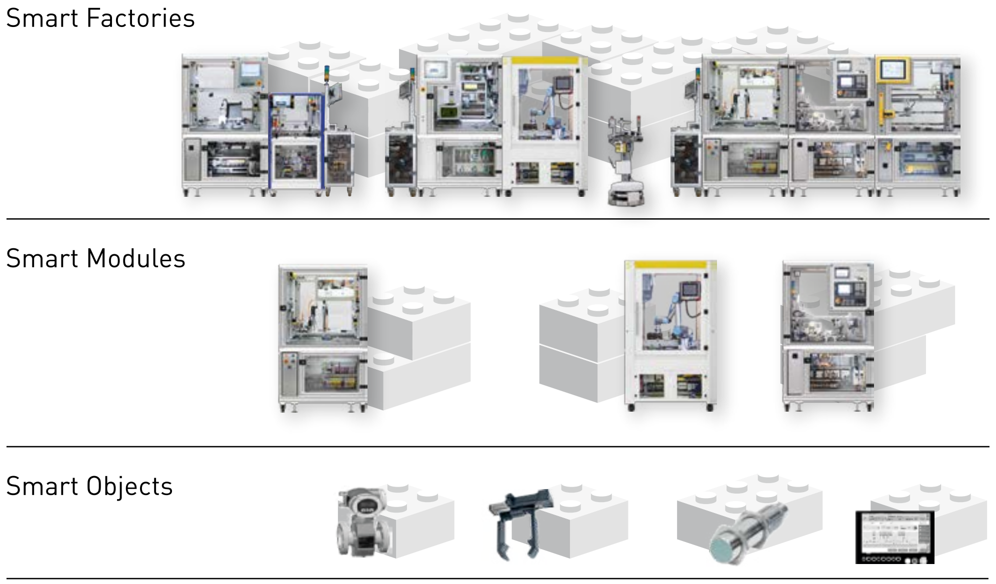


Figure 3:
Modular structure of a I4.0 system

Every module used in the system architecture, to the extent possible, possesses an intelligence. This feature includes as a minimum the ability for self-description (e.g., configuration, master data) and, in the best case, a computing unit (e.g., PC or SPS) that allows automated action. These intelligent modules allow for rapid retooling and return to operations (Req't. 2.1) by partially performing activities themselves. This form of distributed intelligence supports the implementation of complex manufacturing processes (Req't.1.2).

The system architecture specifically focuses on the description of the interfaces between the modules. As mentioned above, modules are described according to the functionality they provide. In the context of interface analysis, to meet the demand for customized networking the focus is on communication interfaces for digital data transfer (Req'ts. 2.2 and 3.1) and information exchange. Module interfaces for the physical exchange should also be specified from a mechanical profile. The power supply to the modules is described in the supply profile. To fully exploit the human potential, the modules also describe the interaction profile for exchanges with humans. The system architecture then provides an integrated definition of the modules from several profiles in a "fact sheet" (Table 1).

Table 1:
Specification of modules in ***SmartFactory***KL system architecture

Module specification:	*[Name]*
Class of module	*Description of the underlying class (e.g., IT system, assembly station)*
Specification "Functionality"	*Description of the module's functionalities*
Specification "Communication"	*Description of (digital) interaction/communications with the surroundings (e.g., services, protocols)*
Specification "Mechanical"	*Description of the physical interaction with the surroundings (e.g., transfer point for materials, dimensions)*
Specification "Supply"	*Description of the operating power requirements of the module (e.g., power consumption, required air pressure)*
Specification "Interaction"	*Description of possible interaction with humans (e.g., HMI, user interfaces)*

6 see http://smartfactory.de/wp-content/uploads/2017/08/SF_WhitePaper_1-1_EN.pdf

The ***SmartFactory***KL system architecture is divided into four main layers that group the different types of modules. The main layers include: product layer, production layer, integration layer, and IT system layer.

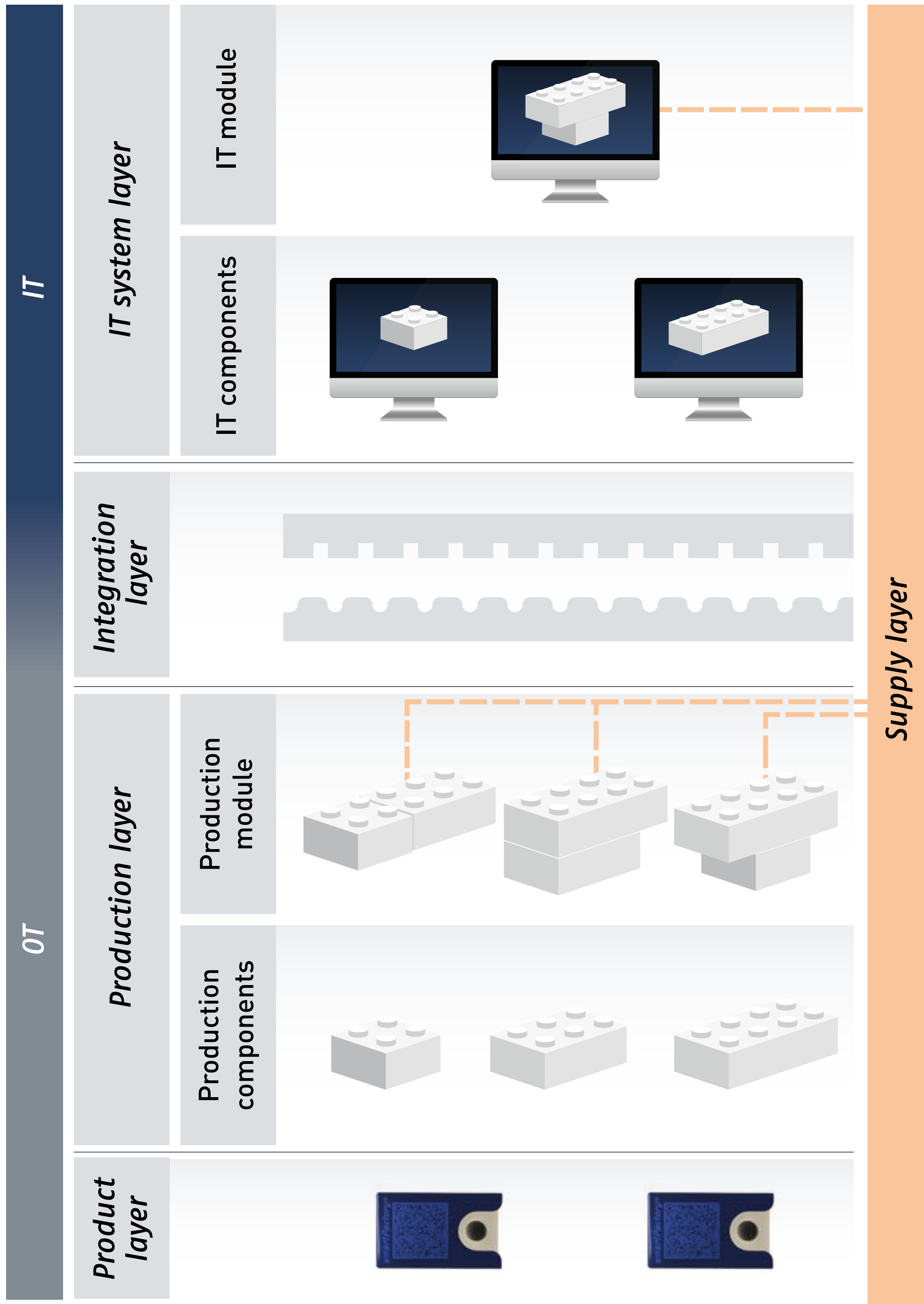


Figure 4:
Overview of ***SmartFactory***KL system architecture

The product layer includes all products manufactured.The product to be manufactured is the only module class in this layer. The production level combines all types of modules used to produce the product. These production modules can be automated production modules, manual workstations or a logistics system. The production modules can be divided into the production components from which they are constructed. The production modules and production components form a sub-level of the production layer. The integration layer is the link between the physical I4.0 plant and the higher level IT systems or, the shop floor and the IT. It groups all modules that make up the communication connection, for example, the communication bus. The IT system layer is the digital pendant for the production layer. It includes all IT modules that provide production services, for example, MES, LVS, or ERP systems. Because larger software applications are usually composed of several services, another sub-level is added. The IT components in the sub-level describe the individual functionalities.

In this model, as a further refinement of the first version of the white paper, the supply layer is no longer an independent layer but a link to all layers. This presentation increases the significance of this cross sectional subject. In production, these intermediary supply components include the power components for the manufacturing stations and the IT networks. Additionally, the IT system layer and the production layer are further defined. It is now possible to specify the modularity and interfaces within the manufacturing stations and IT systems. This allows a more detailed consideration of the functions offered by the respective production module or production component. Furthermore, it creates the possibility of a refined differentiation between value adding and non-value adding activity. This approach specifically enables the description of logistics systems and the distributed I4.0 assets. Whether a logistics module or a logistics component within a production module, the approach allows a detailed description of functionalities. The core function of a logistics module is transport, while a logistics component represents only part of a production step. Figure 4 presents a combined overview of the layers.

The ***SmartFactory***KL system architecture arranged in the Rami 4.0 concept[7] focuses on the "life cycle value stream" dimension and the "Production" and "Maintenance and Use" sections. In the context of the hierarchy levels, the system architecture addresses "work centers" to" "field devices" and refers to all levels except for the "business" level (Figure 5).

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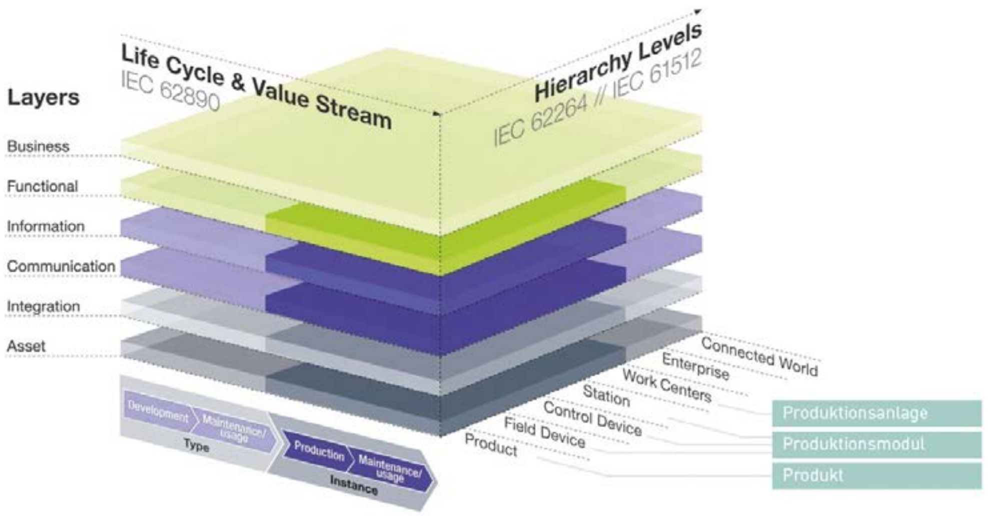


Figure 5:
The RAM I4.0 - displayed as three-dimensional Model – and the ***SmartFactory***KL System architecture for Industry 4.0 Production systems are compatible

Image source:
© Plattform Industrie 4.0

The requirements derived in Section 2 for an Industrie 4.0 system architecture are considered in the system architecture developed below: The architecture defines the application of Industrie 4.0 technologies in such a way to enable an agile response to new requirements. It describes which profiles (functionality, communication, mechanics, power, interaction, etc.) are to be considered for each layer of the architecture and the modules it contains.

Specification Product Layer:

In traditional mass production, there is no focus on the availability of digital product data. This is because only a few variants are ever produced in pre-defined processes over the life cycle of such products. As the product options increase, the importance of product data also increases.

The prerequisite for production with a high number of variants or custom manufacturing is the digital storage of the individual order parameters for the respective product. Only with this data can I4.0 systems read the required parameters and adjust the process for the new order (Req't. 1.1). The different variants, in some cases, will require different production steps and different material flows (Req't. A1.2).

The association between the product and its data must be maintained throughout the production process and, if necessary, expanded and updated. This creates a digital image of the product (the so called "digital twin"). The horizontal networking of the I4.0 plant is another prerequisite for the transfer, for example, of product-related actual production measures.

The production of piece goods initially requires a product reference to enable a unique identification of each product. As the product passes through a defined operational sequence, it is possible to make a comparison of the required manufacturing steps and the services offered in the I4.0 system. The I4.0 units then make the specific parameter setting with respect to the product. The product reference also sets conditions for tracking within the factory and for storing data throughout the product life cycle.

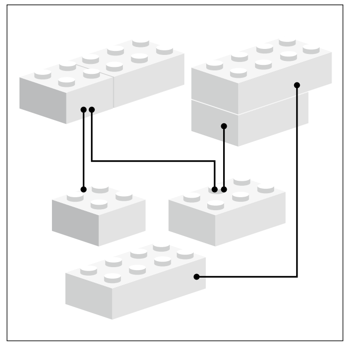
The following aspects are to be defined when specifying a module for the product profile:

Table 2:
Product layer

Module specification	*Product XY*
Class of module	Product
Specification "Functionality"	• Possible to store functionalities directly on the product (production data for horizontal integration, etc.)
Specification "Communication"	• Information model describes the product characteristics (product configuration, attributes, identification number) • Information model describes production steps to include target parameters (for example, NC programs, target storage period, etc.) • Information model describes completed manufacturing steps to include. actual parameters (for example, energy consumption, actual tolerances)
Specification "Mechanical"	• Description of external product dimensions for the logistics (for example, grip robots, work piece carriers, etc.) • Description of the position and method for reading and updating the product reference (for example, position of the QR code or RFID tags)

Module specification	*Product XY*
Specification "Supply"	*(Generally, no power required for the module)*
Specification "Interaction"	*(Generally, no separate HMI needed for vinteractions)*

Specification Production layer:

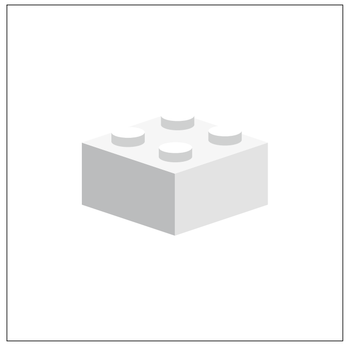


With more variants and ever shorter life cycles, the importance of flexible I4.0 plants is growing. In particular, the fast, cost efficient retooling and operation of I4.0 plants leads to increasing demands on the means of production. A solution to this problem presents itself with the modularization of an I4.0 plant with production modules or components (Req't. 2.1). Modularization presupposes three aspects. First, it encapsulates a specific functionality. To ensure the flexibility of a modular I4.0 plant, the module must be defined by a standard modular interface. Also for additional definition, the module requires interaction between modular components. If these requirements are met, modularity creates the preconditions for integrating a new production process with the minimal physical configuration effort.

The basis for future production is a service-oriented architecture for comparing plant services to the product being manufactured. To implement flexible manufacturing functionalities, each system also requires a self-description capability (Req't. 1.1). This forms the basis for the creation of functionalities that can be automatically connected to a production service. Further insights on the self-description of administrative shells in I4.0 plants is provided in "Example of RAMI 4.0-administrative shell transfer to ***SmartFactory***KL system architecture for Industrie 4.0 production plants"[8].

8 see http://smartfactory.de/wp-content/uploads/2017/11/SF_WhitePaper_2-1_EN-1.pdf

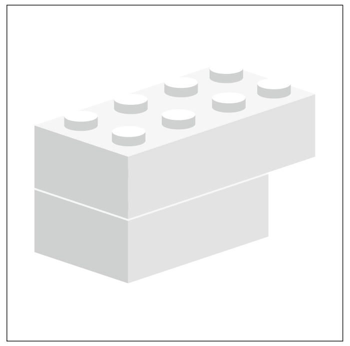
Specification Production component:



Despite the introduction of cyber-physical systems to manufacturing and the associated abandonment of the automation pyramid, there are still logical hierarchy levels. At the lowest level, a production system consists of an intelligent modular component. Such a module describes only a part of a production process and cannot fully capture the functionality of a module. It encapsulates elementary production functionalities, for example, a linear axis transport path. It can be distinguished between value adding and non-value adding functionalities. Value-adding activities related to the production of piece goods are operations such as drilling and assembling; the non-value adding activities are generally logistical operations. Overall, the target in production is to minimize the share of non-value adding activities.

Aggregating production components to higher-level services implies the need for a certain level of self-description. In addition to the unique product reference, there is a clear reference or an administrative shell for the production component. The shell contains all production relevant data and automatically reports to the higher-level system, the cyber-physical production module (CPPM).

Specification Production module:



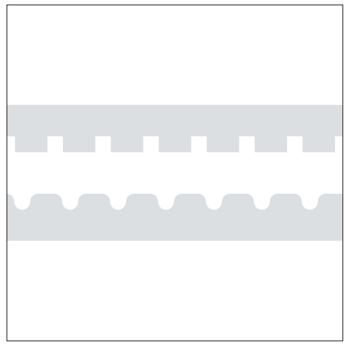
The definition of a production process occurs at a higher hierarchy level. Flexible and modular factory structures comprise at the lowest level the combination of several production components (CPS). When production components are aggregated for some functionality, the result is a cyber-physical production module. These modules orchestrate elementary production functions into a higher-level service and instantiate the specific manufacturing, assembly, test, or handling process to be performed. The interfaces (at the mechanical, electro-mechanical, and information systems level) are standardized. These comprehensive specifications ensure interoperable combinations of production modules. Several CPPMs are linked to form a cyber-physical production system that maps the entire process (Figure 4).

The I4.0 plant must be able to record the assigned production parameters for the product and set the necessary parameters before it can carry out the process. The modules deliver their functionality as a service and adapt to the required parameters of the product. Both CPS and CPPM can be placed in operation via plug & produce. Furthermore, the CPPM enables automatic detection and evaluation of plant topology. The practical implementation of a modular I4.0 plants requires a new concept of certification. The white paper "Safety of modular machines" presents a solution to this problem[9].

Table 3:
Production layer

Module specification	*for example, a milling module*
Class of module	Production module
Specification "Functionality"	• Description of service with, as a minimum, the functionality, expected input parameters, and output result
Specification "Communication"	• Information model for description of production module attributes (production module configuration, attributes, identification number) • Information model for description of functionality (for example, manufacturing sector, type, etc.) • Information model for description of production component (for example, manufacturing sector, type, etc.) • Information model for product • Mechanism for read and write access to the product reference • Mechanism for detecting plant topology • Mechanism for detecting component topology
Specification "Mechanical"	• Description of the basic design of the production module (for example, external dimensions) • Description of the position and method for reading and updating the reference for the production module (for example, location of a QR code or RFID tag)
Specification "Supply"	• Description of required supply and management functions (for example, compressed air) • Described transfer points for the product
Specification "Interaction"	• Standard Human-Machine Interfaces, permanently installed or with mobile access. They enable the control of the module, as well as the retrieval of status information

Specification Integration layer:



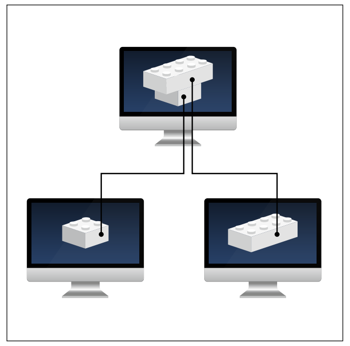
The networking of all machines and, especially, the IT systems poses a great challenge to the vendor-independent plant. Transparent production presupposes that all systems are able to communicate among themselves (Req't. 3.1). A standardizing service is responsible for the integration of the data interface between IT systems and production modules. The system is based on the principles of service-oriented architecture. The user of a service subscribes to the information that is published by the service provider. Among the I4.0 components, equivalent to that principle, a service contract is concluded between the interacting service provider and the user. This contract enables control terminals to network with the higher-level IT system and, in this way, effect the vertical integration of production. Additionally, the integration layer symbolizes the transition between automation and IT. It supplements the layer IT security and acts as an agent or broker for the exchange of information/data packets.

All relevant data and setup parameters are combined in a uniform representation scheme. This prevents the use of a large number of proprietary interfaces between information provider (module) and information user (IT system). The IT system can access information and has read/write access to change setup parameters. A proper Industrie 4.0 module exchanges status information and historical data with the higher-level IT systems such as MES. This requires access to the production and IT levels as well as a uniform semantic description of the modules and products.

Table 4:
Integration layer

Module specification	
Class of module	Integration layer
Specification "Functionality"	• Standardized data format • Security interface (firewall) • Broker for information/data packet exchange
Specification "Communication"	• Information model for production module • Information model for product reference • Information model for supply module • Communication module for read/write access from the production layer • Communication module for read/write access from the IT layer
Specification "Mechanical"	*(Normally unnecessary because the hardware used has a minor impact on the integration interface)*
Specification "Supply"	*(Normally, the hardware power supply is standardized, so there is no need for a separate specification)*
Specification "Interaction"	• Description of user roles

Specification IT systems layer:



The changebility demanded in the future requires more than merely a modular approach to production. Even the connected IT systems must be constantly adapted to the new requirements over the service life. First, this involves exchanging or updating the existing software with newer versions (for example, MES updates). Second, a subsequent integration of specialized services that need to interact with existing systems is needed (for example, the use of AI for production controls).

The flexible, fast adaption of the IT environment also requires a modular approach with vendor-independent, open communication interfaces and information models. This ensures the possibility for exchanges between the I4.0 plant and other IT systems. The integration layer assumes a substantial role in this since it can convert proprietary interfaces to a uniform format. Also, it is able to exchange data between IT systems following the appropriate regulatory frameworks.

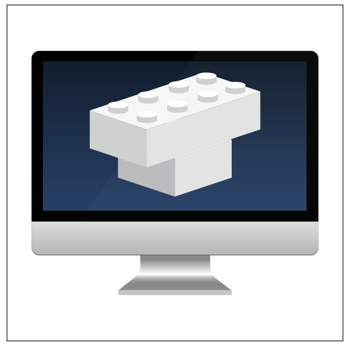
The IT system layer distinguishes two types of modules that can be assigned to it:

Specification IT component:

IT systems encapsulate elementary services, analogous to the production components of the production layer. The functionality of every IT system must be known as well as a specification of the services provided and messages exchanged.

In practice, IT systems are more likely found in self-developed solutions created in support of existing systems. These are especially well suited for solving company-specific problems. Planning tools for special logistic processes are a good example of these systems. Otherwise, IT systems in the system architecture serve a logical grouping of functionalities in the IT module. Modern ERP systems are usually built from separate IT systems like material resource planning, personnel administration, and controlling.

Specification IT module



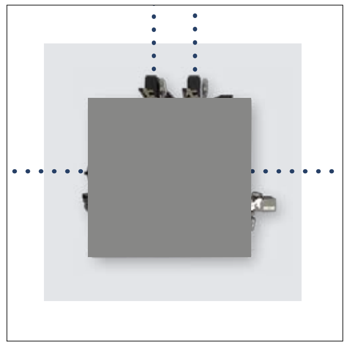
IT modules aggregate separate functionalities of the IT systems to form an integrated system for example, ERP systems or MES systems. A standard description of the interfaces and uniform communication is essential even for these modules. IT modules can be installed in a separate IT infrastructure or as cloud services, used over the internet and connected to the integration interface.

The following aspects are to be specified for the modules of the IT system layer:

Table 5:
IT layer

Module specification	*for example, ERP systems or "inventory management"*
Class of module	IT module or IT system
Specification "Functionality"	• Description of service with, as a minimum, the functionality, expected input parameters, and output result
Specification "Communication"	• Technical description of service provided (for example, protocol used, address of the service, transfer parameters, return values) • Information model of the exchanged data (for example, attributes of the data packet, unit values)
Specification "Mechanical"	*(Normally unnecessary because the hardware used has a minor impact on the versatility of the software)*
Specification "Supply"	*(Normally, the hardware power supply is standardized, so there is no need for a separate specification)*
Specification "Interaction"	• Description of the user interfaces of the module and the available functionalities for each user role

Specification Supply layer (cross-section layer)



Rapid conversion, especially, with regard to the exchange of modules requires a standardized, modular infrastructure (Req't. 2.1). This implies the supply and management functions, which include energy supply, compressed air supply, data routing as well as an integrated control of the security and safety functions. Only through the additional standardization of the production infrastructure is the Plug & Produce paradigm possible, which enables a rapid exchange of modules to adapt to new products or product variants. In this way also, the integrated operational readiness is assured.

Table 6:
Supply layer

Module specification	*for example, compressed air*
Class of module	Supply layer
Specification "Functionality"	• Supply to production modules with required input values • Data routing • Safety controls
Specification "Communication"	• Firewall on physical layer • Information model power supply media • Data exchange
Specification "Mechanical"	• Connection to the production modules
Specification "Supply"	• Media
Specification "Interaction"	• Description of user roles

The previous section introduced the ***SmartFactory*KL** system architecture and discussed the individual layers along with the aspects required to be specified at each level. The descriptions of the communication interfaces play an important role, especially, as they are essential for the digitalization of production and realization of a modular, flexible I4.0 plant. Communication must be possible throughout, from the product to the IT system layer in the cloud. In other words, continuous vertical integration is essential.

The specification of the supply and mechanical interfaces are most important in the production and product layers, because this is where objects are physically exchanged. At all of the other layers, these interfaces play a subordinate role because the design and power supply (e.g., server hardware) is mostly standardized and has no influence on the modularity of the software service.

As a further development of the first version of the white paper, this version deepens the elements to be specified and identifies classes (see types or roles) of modules at each layer to better describe the components required for real modularity. It is also possible using this approach to specify logistic modules in addition to production modules; and, to modularize not just the separate I4.0 plants, but entire production halls with multiple lines.

4. Instantiation

***SmartFactory*KL** exhibits the world's first vendor-independent, Industrie 4.0 production plant and shows just how high quality, flexible manufacturing can be efficiently implemented even for a lot size of one – whether in an existing production operation or a Green Field. Uniform interface standards enable a vendor independent link to the production modules, logistic systems, supply infrastructure, and IT systems.

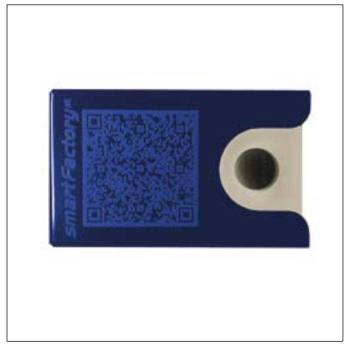
In addition to the fully automated plant, a manual assembly station has been integrated. This allows the integration of the important topic "work of the future and the introduction of the developments in human and machine interaction" into the demonstrator. The central issues for the factory of the future are addressed and implemented: plug & produce, predictive maintenance, scalable automation, and support for the worker. Since 2017, the I4.0 plant has operated under a completely new layout: divided into several manufacturing lines and the manual work station. The cells are connected by a flexible transport system that distributes the products to be manufactured from station to station. The addition of this functionality shows that the ***SmartFactory*KL** approach not only applies to one production line, but carries over to several locations because of the decoupled logistics.

Figure 6:
The ***SmartFactory*KL**
Facility 2018

Image source: A. Sell

The system architecture is presented below using the example of the ***SmartFactory*KL** pilot facility enriched with detailed specifications. The specification is an evolution from the first version of the white paper.

4.1. Product



The I4.0 plant at ***SmartFactory***KL produces personalized business card cases. Designed with four components (bottom plate, retaining spring, lid/cover, and inlay), the product allows a variety of customization options. First, the color of the lid is selectable and the product can be customized with an engraving on the bottom plate and a laser-engraving on the metal lid. Additionally, individual inlays can be inserted, if desired.

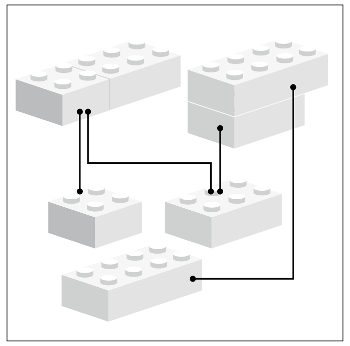
Figure 7:
Personalized business card case (left) as pilot product of the ***SmartFactory***KL with individual components: base plate, holding spring, inlay and lid (right)

Specification of the product

Table 7:
Instantiate product layer at ***SmartFactory***KL

Module specification	*Business card case*
Class of module	Product
Specification "Functionality"	***"Digital Product Memory – RFID"*** • Allows information to be passed among the different production modules and enable the horizontal integration of the I4.0 plant.
Specification "Communication"	***"SF information model for product"*** • Information including order number, order date, assembly status, priority, manufacturing steps, power consumption per module, duration of operation, lid color, customer data for QR code (laser-engraved) and bottom engraving ***Mechanism for read/write access on the digital product memory*** • Customer-specific product parameters are stored in the digital product memory when the order is received • Siemens MDS D460 – ISO 15693, 2048 Byte user memory • The RFID-Chip is subject to versioning with X the major share and Y the minor share (following the common form X.Y). All minor versions are compatible within the same major version • ASCII character set with 128 characters
Specification "Mechanical"	***RFID-Tag (13.56 Mhz)*** • The RFID tag is firmly integrated into the master component of the product (base plate)
Specification "Supply"	RFID supplied with power via induction
Specification "Interaction"	–

4.2. Production layer



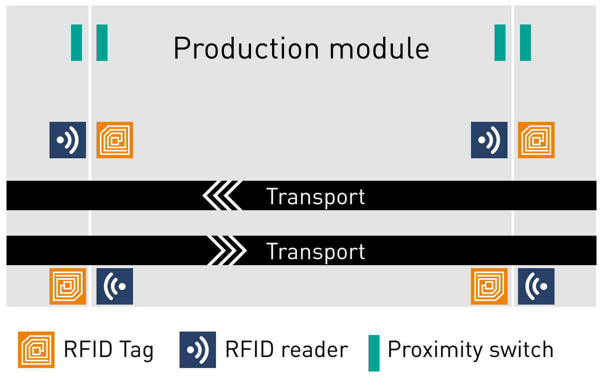
Up to ten different production modules can be linked to a production process as required for the production of a custom business card case. The modules encapsulate various production steps from handling through quality control to logistics. In addition to the automated modules, the manual work module allows each of the functions of the individual modules to be replaced while supporting the worker in the execution of his tasks. The plant is divided into four different production lines which are linked by the driverless transport module. This clearly shows how the Industrie 4.0 plant can also function as a distributed system. The digital product memory acts as a means of integration for the horizontal networking between plant sections.

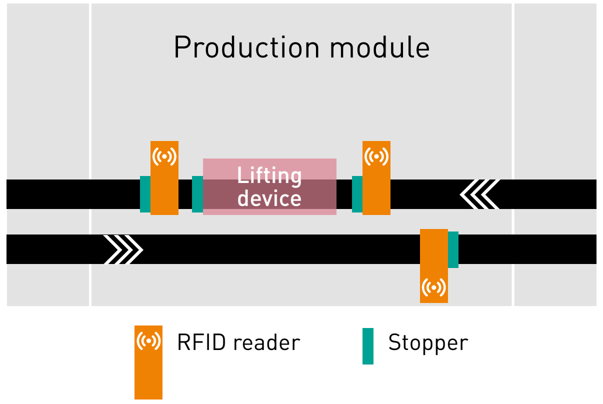
Figure 8:
The production process to manufacture the business card case currently includes up to eight different production modules.

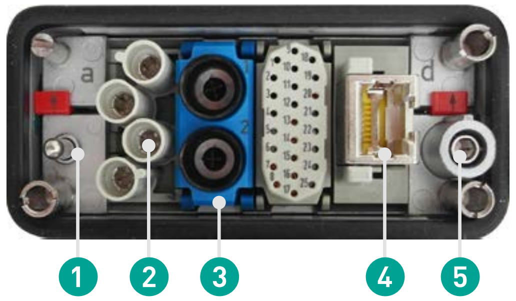
Specification of the production module

Table 8:
Instantiation of production layer at *SmartFactory*[KL]

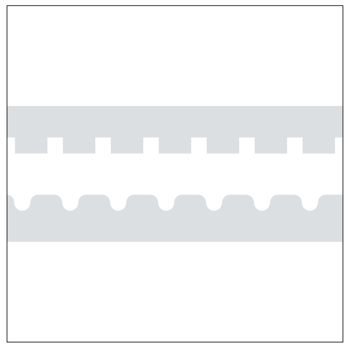
Module specification	
Class of module	Production module
Specification "Functionality"	***"SF production module"*** • Store the work piece carriers, engraving the bottom plate, inserting the retaining spring, pressing the lid, laser the lid, weigh the product, optical control of the laser QR codes, insert inlays ***"SF transport system"*** • Modular transport system with two revolving conveyor belts, locking devices and defined transfer points for the products: 1. Open gate: product passes 2. Closed gate: diverts forward and return belt ***"Manual work station"*** • Manual assembly station can replace the functions of the production module and support the worker with innovative technologies ***"SF logistic module"*** • Robotino – driverless transport system 1. Scan surroundings via laser scanner 2. Control via MES system ***"SF interface module"*** • Docking Station 1. Connection between logistic module and manufacturing module 2. Non-contact loading of the SF logistic module ***"SF safety functions"*** • Emerg. Stop • Ejection gate-Left • Ejection gate-Right • Protective door

Module specification	
Specification "Communication"	***"SF information model for production module"*** • Modules have exactly one open access OPC UA server. This forms a uniform, defined information model • Information on: properties, production status, operating status, topology (neighboring module) as well as resource demands and usage of the production module • describes a flat list of data whose types are compatible with IEC 61131-3 and common high-level languages (C#, C++) ***"SF information model for product"*** See Specification of the product ***"SF Topology recognition"*** • Assembly group of a RFID reader, RFID tag as well as two proximity switches for recognition and unique identification of the neighboring production module.  • Information model for description of functionality (for example, manufacturing zone, type, etc.) • Information model for description of production component (for example, manufacturing zone, type, etc.) • Information model for product

Module specification	
	"SF product tracking" • Based on RFID (13.56 Mhz) • When the product enters a production module, all product parameters are read out on the digital product memory • Before leaving the module, the digital product memory is updated regarding the production status, amongst other things 
Specification "Mechanical"	***"SF basic structure"*** • Module dimensions [m]: L 1.20xB 0.80xH < 1.90

Module specification	
Specification "Supply"	**"SF modular socket"**  1 Protective conductor 2 400V three phased AC current 3 Compressed air 4 Industrial Ethernet 5 Protective conductor
Specification "Interaction"	**"SF Augmented Reality Application"** • Information projected via the Hololens to the worker's glasses is tailored and preprocessed using artificial intelligence tailored to the needs of the operator

4.3. Integration Layer

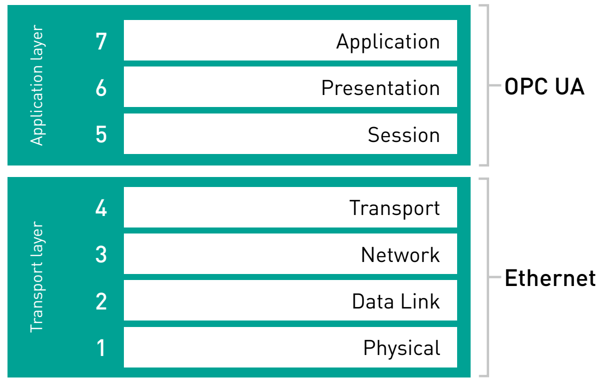


The integration layer has the task to collect the data of the production modules, which is provided during the supply layer, then aggregate the data and provide it to the comprehensive IT systems. This allows for an bilateral exchange between production level and IT systems. Through a standardized communication protocol, operating and product data from the production layer are recorded, enriched and saved in the integration interface in a structured manner.

The information supply of the higher IT system layer follows the basic principle of a service-oriented architecture: any information can be published by the information interface and can be subscribed to by the IT systems if needed without having to implement various individual 1:1 interfaces between the production modules (information provider) and the IT systems (information user).

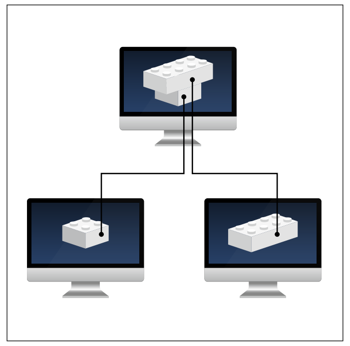
Specification of the integration interface

Table 9:
Instantiation of integration layer at SmartFactory[KL]

Module specification	
Class of module	Integration layer
Specification "Functionality"	• Standardization of the data format • Security interface (firewall) • Agent/Broker for information/data packet exchange
Specification "Communication"	**Communication protocols (in the OSI reference model):** • Transport layer: Ethernet • Application layer: OPC UA (IEC 62541)  **Communication protocols:** Many communication protocols are possible, e.g.: • MQTT • RESTful-web service • SOAP-web service

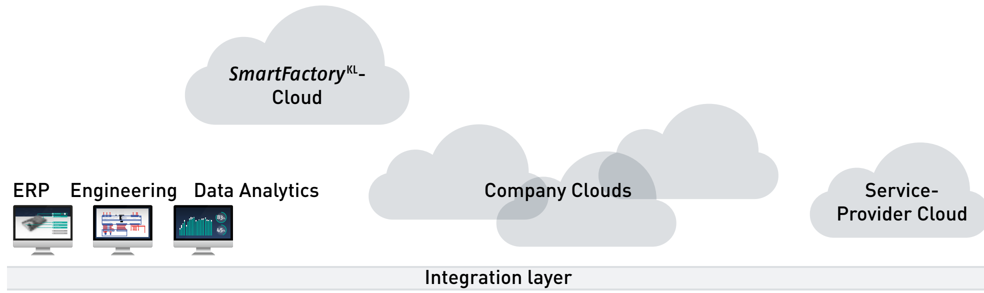
Module specification	
	"SF Information model for production modules" See specification of the production modules ***"SF Information model for products"*** See specification of the product
Specification "Mechanical"	*(Normally unnecessary because the hardware used has a minor impact on the integration interface)*
Specification "Supply"	*(Normally, the hardware power supply is standardized, so there is no need for a separate specification)*
Specification "Interaction"	• Description of user roles

4.4. IT system layer



Enclosed, heterogeneous software components of the IT system layer enable dynamic monitoring, control, planning, analysis and simulation of the production plant. In the ***SmartFactory***KL pilot plant, the following IT systems are currently implemented: order planning (ERP), order control (MES), plant engineering (PLM), data acquisition and data analytics (Big Data) as well as remote monitoring/maintenance (Figure 4).The ***SmartFactory*** KL cloud, as a higher-level cloud platform has access to the diverse IT systems of different suppliers. This allows, for example, the I4.0 plant to be checked for anomalies.

Figure 9:
IT systems at
SmartFactoryKL



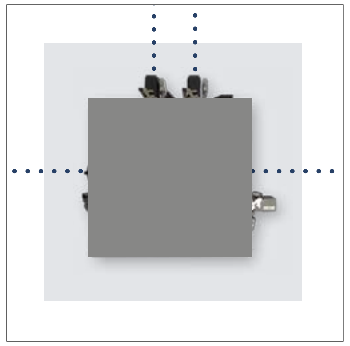
Specification of the IT system interface

Table 10:
Instantiation of the
IT layer at
SmartFactoryKL

Module specification	
Class of module	IT module or IT system
Specification "Functionality"	• Description of service with, as a minimum, the functionality, expected input parameters, and output result
Specification "Communication"	***"SF Information model for production modules"*** • See Specification of the production module ***"SF Information model for product"*** • See Specification of the product ***Communication protocol for read/write access:*** • See Specification of the integration interface • Information model of the exchanged data (for example, attributes of the data packet, unit values)
Specification "Mechanical"	*(Normally unnecessary because the hardware used has a minor impact on the versatility of the software)*
Specification "Supply"	*(Normally, the hardware power supply is standardized, so there is no need for a separate specification)*

Module specification	
Specification "Interaction"	• Description of the user interfaces of the module and the available functionalities for each user role

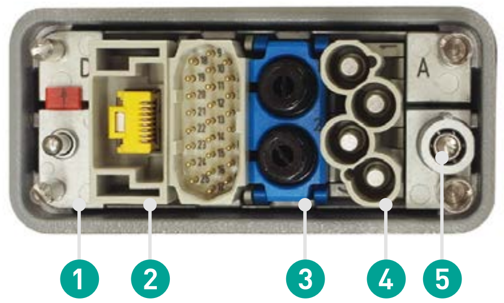
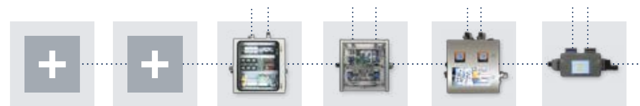
4.5. Supply layer



The supply layer enables a standardized connection and supply of the production modules. Currently, there are four vendor-specific but compatible supply modules, which provide the connected production modules with pressured air and three-phase current via the "SF modular plug" connect them to the security function and enable the communication between the production layer and integration layer by means of Ethernet.

Specification of the supply module

Table 11: Instantiation of the supply layer at *SmartFactory*[KL]

Module specification	*Power supply module and modular plug*
Class of module	Supply layer
Specification "Functionality"	• Supply of production modules with required media • Data routing between supply modules and production modules • Safety function controls
Specification "Communication"	***"SF Information model for supply module"*** • Information via media, for example, power consumption
Specification "Mechanical"	***"SF modular plug"***  1 Protective conductor 2 Industrial Ethernet 3 Compressed air 4 400V three phased AC current 5 Protective conductor ***"SF supply module"*** • The supply modules enable the scalability of the I4.0 plant. New production modules can be flexibly integrated or removed. 
Specification "Supply"	• 400V AC current • Compressed air • Ethernet
Specification "Interaction"	• Description of each user role

Today, the specification of the system architecture enables a comparison between the ideal model and the ***SmartFactory***KL implementation. In the context of the product layer, the I4.0 plant at ***SmartFactory***KL provides a feasible solution for horizontal networking via the digital product memory. This enables the completely decentralized control of the production process. Other approaches to horizontal integration would also be possible through direct communication between the modules. A difference between the developed system architecture and the I4.0 system is manifested in the production components of the production layer. Until now, the functions were encapsulated directly at the level of the cyber-physical production modules. The modularization of the production modules based on components (CPS) places new requirements on the I4.0 facility. ***SmartFactory***KL implemented a prototype of these encapsulated functionalities at the module level. In a follow-on step, this must be refined and transferred to the production components. This further requires a definition of the specific functionalities and the self-description capability the components must provide in order to create a higher level service. A standard interface is lacking for the reconfigurability of the I4.0 plant as well as a fixed definition of the interaction between production components. In the context of the production modules, more flexible service architectures are conceivable that could enable increased vertical integration. Especially worthy of note are the operating systems of the production modules, which are still vendor-dependent and heterogeneous. The use of Augmented Reality and AI solution assists the human worker around this problem in production. The I4.0 plant already provides a multitude of implementation options regarding the supply, integration, and IT layers. Noteworthy is the implementation of the modular IT system that enables cloud-to-cloud communication and the aggregation of information in a form useful to the person.

5. Summary and Outlook

5.1. Summary

This white paper describes the advance development of the SF system architecture for I4.0 plants. The system architecture assists the user to design and implement an I4.0 plant in a greenfield situation. Thanks to the integrated modularity and the specification of interfaces, the I4.0 plant can be assembled with vendor-independent building blocks. Furthermore, it achieves the necessary versatility for the future market requirements of shorter life cycles and customized products.

The partners of ***SmartFactory***KL have evaluated the architecture and shown the feasibility with this exemplary realization. Standardization and best-practices used in the implementation at ***SmartFactory***KL are introduced and explained in this white paper.

In this further development of the first version of the white paper, in particular, we address the role of humans and logistics in the system architecture. For this purpose, aspects to be specified in order to facilitate the interactions between human, IT and machines at each layer have been defined. Additionally, the production "logistics" component has been expanded to standardize the material transfer across multiple production lines. It also takes the existing specifications of the first version into account to standardize the structure of production modules.

A standard structure within the production modules is now a topic to be further developed in the future. In more concrete terms, this means specifying the types and interfaces of the production components, to create versatility within the manufacturing modules. This form of modularization is less focused on the rapid replacement of manufacturing modules, and more concerned with the engineering-process of new modules.

Future work will further refine the interfaces and the information models necessary for communication. The production modules at ***SmartFactory***KL represent Industry 4.0 components. In this respect, the realization of the administrative shell is an important goal of the ***SmartFactory***KL partners[10]. At the Hannover Messe 2018, ***SmartFactory***KL demonstrated how so-called edge devices are used as possible hardware for uniform interfaces with which even existing plant systems can be digitally integrated. The modularization of the I4.0 plant raises questions concerning the safety and security of the modifiable I4.0 plant, which are also topics of current interest in the work of the ***SmartFactory***KL partners[11].

10 see http://smartfactory.de/wp-content/uploads/2017/11/SF_WhitePaper_2-1_EN-1.pdf
11 see http://smartfactory.de/wp-content/uploads/2018/04/SF_WhitePaper_Safety_3-1_EN_XS-1.pdf

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