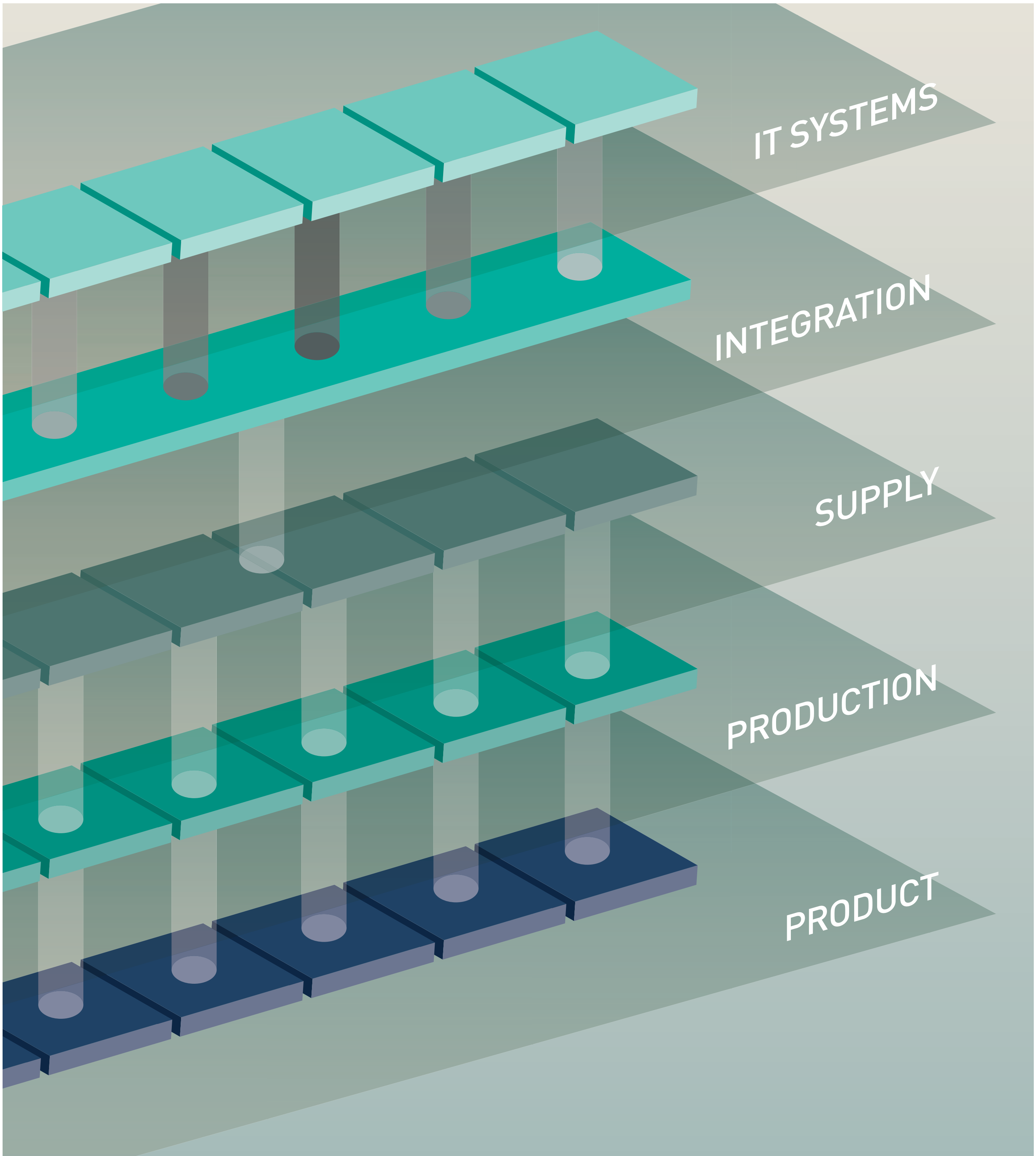


# *SmartFactory*KL System Architecture for Industrie 4.0 Production Plants

Whitepaper SF-1.1: 04/2016

smartFactory KL®

**Abstract**
This white paper describes a system architecture for Industrie 4.0 production plants in the discrete, loosely connected flow production. The system architecture serves as solution pattern for the conception of modern production plants, which are characterized by mechatronic changeability, individualized mass production and internal and external networking. The system architecture is complemented by a set of cross-manufacturer specifications on mechanical, electromechanical and information technology-related aspects, which were developed, applied and demonstrated by means of the example of the pilot plant of the ***SmartFactory*KL**. In conclusion, the system architecture is classified in the Reference architecture model Industrie 4.0 (RAMI 4.0) of the Platform Industrie 4.0.

**Keywords**
Mechatronic changeability, individualized mass production,
internal and corss-company networking

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# 1. Introduction

The term Industrie 4.0 is a synonym for the production of tomorrow, which is characterized by the digitalization of the work processes, increasing networking and modularization of intelligent machines, products and equipment.

Industrie 4.0 is thus seen as the technological answer to current and emerging global-economical changes, such as shortened product life spans and increasing customer-oriented value. Especially the discrete production is opposed with a stronger demand for customer-oriented products and product variants. The trend towards smaller batch sizes with larger varieties quickly pushes classic production concepts to their economical and technological limits. Especially consumer goods are under immense innovation and cost pressure, since they have a relatively short usage duration and have to be available at all times in many variations.

In industrial practice, there are some examples in which products are manufactured individually and upon the customer's request. Adidas[1] and Nike[2] have pilot projects, which strive for the economical production of sports shoes with personalized design. Within the food industry, providers such as myMüsli[3] make it possible to order customer-individual product variants via the Internet. The automotive industry already offers extensive trim options and configuration possibilities to the customer. At Airbus[4], replacement parts are already generated according to demand. The according module information is always digitally available on the worldwide network and is immediately generated on site by means of a 3D printer in order to reduce delivery times and storage costs. It is to be expected that this trend towards a flexible and customer-individual production will increase. The manufacturer who produces in a demand-oriented manner for the customer has the competitive advantage.

In the mentioned examples, the customer individuality is not or only partially achieved by means of the use of flexible production concepts. The mentioned example products can be characterized by the fact that they also have many manual process steps (as for example in shoe and textile production), that only a few process steps are required for individualization (as for example during the dispensing process to produce Müsli) or that the individualized mass production can only be achieved by means of strict and highly complicated production plants (as for example in automotive production).

In order to be able to react appropriately to current and future challenges, new production concepts are needed which fulfill the following three goal criteria:

***1. Mechatronic changeability:*** Production plants are versatile and modularly structured in line with the minimization of downtime and cost reduction during conversion; they can be put into operation quickly and with little effort and can be adapted to new production requirements.

***2. Individualized mass production:*** Production plants dominate the economic manufacture of individualized products and wide-ranging product variants - i. e. small batch sizes - in conditions of mass production.

***3. Internal and cross-company networking:*** Products and production plants, which can communicate, can quickly and with little effort be connected to IT systems and thus enable transparent insight and intervention possibilities to the current production processes - malfunctions can be predicted, processes can be optimized.

The system architecture of the ***SmartFactory*KL** describes the conceptual structure of modern Industrie 4.0 production plants, which meet all previously defined goal criteria. Before the system architecture will be presented in detail in chapter 3, the requirements will be deduced first in chapter 2. The system architecture will be completed in chapter 4 by a set of cross-manufacturer specifications, which were developed and applied by means of the ***SmartFactory*KL** pilot plan. The specifications are used as orientation aid for the design and conception of similar Industrie 4.0 production plants. In conclusion, chapter 5 classifies the system architecture into the *Reference architecture model Industrie 4.0 (RAMI 4.0)* of the *Platform Industrie 4.0*.

1 http://www.adidas.de/personalisieren
2 http://www.nike.com/de/de_de/c/nikeid
3 http://www.mymuesli.com/
4 http://www.deutschlandfunk.de/auftakt-der-cebit-drohnen-sicherheit-und-das-internet-der.766.de.html?dram:article_id=348350

# 2. Requirements for the system architecture

In the following, the previously defined goal criteria "mechatronic changeability", "individualized mass production" and "internal and cross-company networking " will be transferred and substantiated in requirements to the general system architecture. Thanks to the general validity, the system architecture can be transferred to the planning of similar production plants.

## Goal criterion C1 "Mechatronic changeability"

Production plants are versatile and modularly structured in line with the minimization of downtime and cost reduction during conversion, they can be put into operation quickly and with little effort and can be adapted to new production requirements.

### Requirement R1.1 "Modular process components"

The system architecture has to make it possible to build individual production processes from standardized process components with minimum effort. This also implies that new process components can be integrated into existing production processes with minimum engineering efforts. Each process component encloses dedicated production functionalities and is instantiated in a new production module. Production modules can be operated individually or in combination with other production modules. In addition, a loose chain of individual production modules according to the "Plug-and-play" shall be foreseen (cf. figure 1). The arrangement of the production modules is also called Topology. Since the topology may vary, a mechanism is to be planned, which makes is possible to automatically recognize and evaluate the current topology of the production plant.

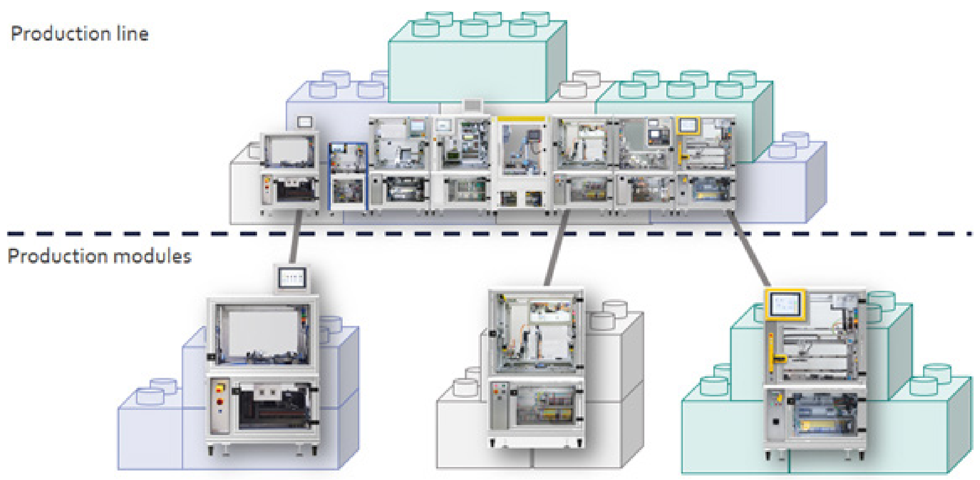



Figure 1:
The system architecture makes it possible to flexibly chain individual production modules per Plug-and-Play in the sense of the goal criterion "Mechatronic changeability"

### Requirement R1.2 "Modular supply infrastructure"

In order to be able to combine production modules to a production process universally and with minimal configuration effort, the system architecture has to provide a flexible supply infrastructure, which takes on essential supply and management functions for the production modules. This includes energy supply, data routing and comprehensive control of the safety functions.

The supply infrastructure itself has to be built modularly in order to avoid sacrificing the flexibility, which was gained by building a production plant, due to complex or rigid infrastructure planning.

## Goal criterion C2 "Individualized mass production":

Production plants dominate the economic manufacture of individualized products and wide-ranging product variants.

### Requirement R2.1 "Integrated product tracking":

The system architecture has to provide a solution which makes it possible to uniquely identify products to be manufactured and to track them within the production process at all times. The solution has to make it possible for the production modules to record and process the production parameters individually.

### Requirement R2.2 "Largest possible product and variant diversity":

The processed imaged in the production module are to be designed in a way that the largest product and variant diversity can be processed by means of parameterization.

## Goal criterion C3: "Internal and cross-company networking":

Information on the production plant and the products to be manufactured shall be available continuously in digital form and in real-time in order to simplify the decision and optimization processes within the producing company as well as between the companies.

### Requirement R3.1 "Integrating interface":

The system architecture has to plan one open interface for loose coupling between the IT systems and the production plant. The information interface has to adapt an integrating function and logically combine all relevant information and setting parameters from the production plant in one unique representation scheme. The connected IT systems have to be granted access to the information and setting parameters of the production plant - while maintaining certain reading and writing rights. One integrating interface is designed to avoid that n:m differently structured interfaces will occur within the production modules (information providers) and the IT systems (information users).

**Requirement R3.2 "Modular IT systems":**

The system architecture has to plan for the flexible integration of IT systems for planning, controlling and optimization of the production plant. New IT systems have to be able to be integrated into the planned interface with as little effort as possible. For this, an enclosure of the IT systems into modular function modules is to be planned, which can be easily integrated and exchanged.

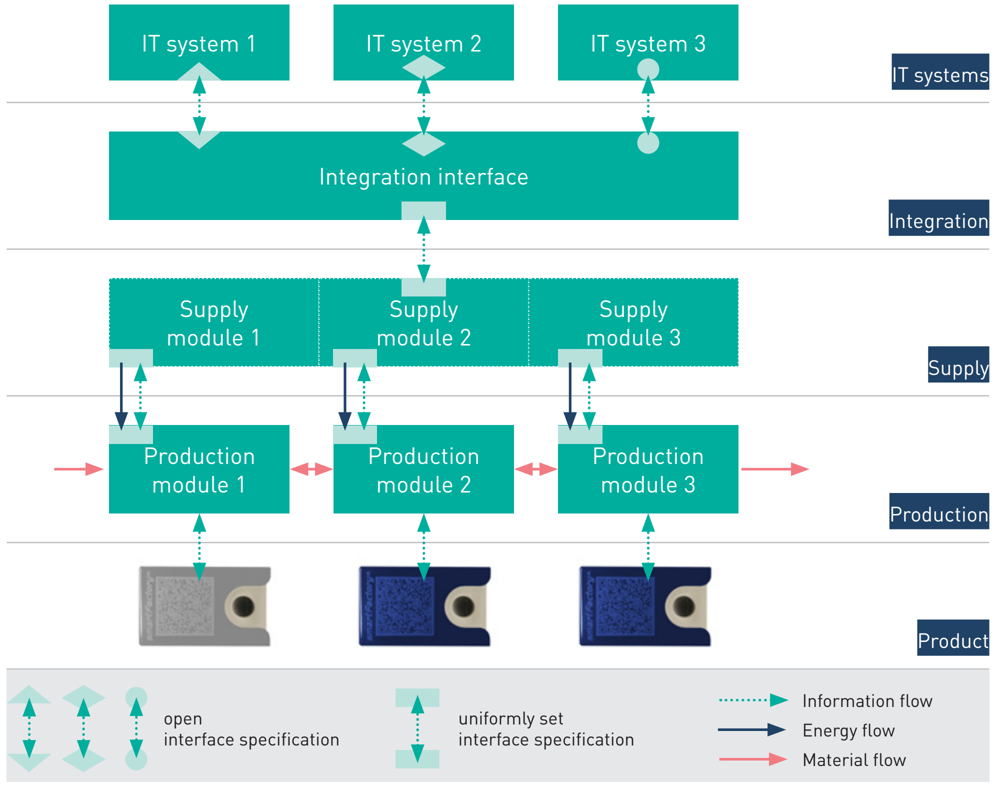
# 3. Conception of the system architecture

Under consideration of the requirements for future production concepts, a general system architecture for Industrie 4.0 production plants is described, which plans for a decomposition of the production plant in five conceptual components (cf. figure 2):

1. ***Product***
2. ***Production layer***
3. ***Supply layer***
4. ***Integration layer***
5. ***IT system layer***

Each component is separated from the others in line with an approach of Separation of Concerns[5] by means of dedicated tasks, functions, characteristics and areas of responsibilities, by which the global dependencies of component-specific elements are reduced. In the following, the individual components of the system architecture are presented conceptually, before a concrete implementation example is described by means of the ***SmartFactory***KL pilot plant (cf. chapter 4).

Figure 2:
System architecture of the ***SmartFactory***KL for Industrie 4.0 production plants




5 IT-Concept, where the different elements of the task are presented in different elements of the solution.

### *3.1. Product*

The economical production of the individual product on conditions of mass production is the goal of the system architecture. The *product* to be manufactured is the starting point for the conception of the production process. The complexity and variants of the product immediately imply the number and configuration of the production modules as part of the production layer.

*Specification of the product*

According to requirement R2.1, the product is equipped with a digital product memory, which makes it possible to track and actively control the production process. The digital product memory consists of a mechanism for automatic identification (short: auto ID) and a referenced information model to store relevant production parameters.

*Electromechanical specifications:*
- Mechanism on reading and writing access to the digital product memory

*Information technology specifications:*
- Information model of the digital product memory

### *3.2. Production layer*

The production layer takes on the actual value-added activity to manufacture the individual product according to a predefined production process. The production process is compiled by combining different production modules.

*Specification of the production modules*

Each production module takes on the execution of a specific manufacturing, assembly, inspecting or handling process. According to requirement R2.2, the imaged process is to be designed as universal and parameterisable as possible in order to be able to use the production module for various products and product variants.

Even though the processes in the specific production modules may differ greatly, comprehensive specifications must ensure the interoperable combination of the different production modules. With this, the requirement R1.1 for a smooth and effortless linking of the production modules according to the "Plug-and-play" paradigm is met. In order to track the current order of the production modules at any time, an automatic topology detection is intended, which is based on auto ID technologies and a unique information model in accordance with the digital product memory.

*Mechanic specifications:*
- Basic mechanical structure
- Transport system

*Electromechanical specifications:*
- Mechanism on reading and writing access to the digital product memory
- Mechanism for recognizing the plant topology
- Connection to the supply infrastructure

*Information technology specifications:*
- Information model of the production module
- Information model of the digital product memory

*Standardized operating concept:*
- Operation states
- Module behavior

### *3.3. Supply layer*

The supply layer ensures the operational readiness of the previously described production modules. The supply infrastructure is flexibly compiled by linking the supply modules.

*Specification of the supply modules*

In order to be able to combine production modules to a production process universally and with minimal configuration effort, a flexible infrastructure according to requirement R1.2 is necessary, which takes on essential supply and management functions for the production modules. This includes energy supply and registration, data routing and security functions. According to requirement R1.3, the supply infrastructure has to be built modularly in order to avoid sacrificing the flexibility, which was gained in building a production plant due to a complex or rigid infrastructure planning.

***Electromechanical specifications:***

- Connection to the production modules

## *3.4. Integration layer*

The integration layer has the following tasks: information exchange between product, production and infrastructure layer on the one hand, and the IT system layer on the other hand. It is implemented by means of n integration interface.

***Specification of the integration interface***

In accordance with requirement R3.1, the integration interface adapts an integrating function and logically combines all relevant information and setting parameters from the production plant in one standardized representation scheme. The IT systems connected to the integration interface receive reading and writing access to the information and setting parameters imaged in the representation scheme via communication protocols.

The basic interaction between the production modules (information provider) and the IT systems (information user) is uniquely and securely controlled according to the basic principle of a service-oriented architecture: a service provider publishes the service he provides (e.g. status information of a production module), possible service users (e.g. ERP system) subscribe to services relevant to them (e.g. status requests). When using the service, service users and service providers interact according to an agreement (service contract), which for example defines frequency, response time, usage costs, authorizations and extent of the provided information. Services which have not been agreed upon or which are not permitted (e.g. more frequently than agreed upon) are not processed.

***Information technology specifications:***

- Information model of the digital product memory
- Information model of the production module
- Communication protocol on reading/writing access from the production layer
- Communication protocol on reading/writing access from the IT layer

## *3.5. IT system layer*

The IT system layer includes all functionalities on computer-supported production planning, control and optimization. The IT system interface creates the interface to the integration layer.

***Specification of the IT system interface***

The IT systems have to be integrated with the integration layer with as little effort as possible. For this, an enclosure of the IT systems into modular software modules according to requirement R3.2 is planned. The communication between the enclosed IT systems and the integration interface is based on standardized information models. The information exchange can be implemented through different communication protocols (according to the interface specification of the respective IT systems).

***Information technology specifications:***

- Information model of the digital product memory
- Information model of the production module
- Communication protocol on reading/writing access

# 4. Instantiation of the system architecture

In 2014, the ***SmartFactory***KL designed a worldwide unique Industrie 4.0 pilot plant for a discrete, loosely-coupled flow production, which meets all previously defined target criteria (cf. figure 3). More than 16 companies from the information and automation technology sector were involved in the development of the pilot plant. The common activity is based on the understanding that the potentials of Industrie 4.0 can only be raised by cross-manufacturer specifications or standards. Similar to the development of the World Wide Web, generalized protocols and information models are needed in order to link production plants with each other and to make the running processes understandable and accessible for the human.

In the following, the previously presented system architecture is applied with the example of the ***SmartFactory***KL pilot plant and enriched with detailed specifications.

Figure 3:
The ***SmartFactory***KL pilot plant for Industrie 4.0 meets the three goal criteria "Mechantronic Changeability", "individualized mass productions" and "internal and cross-company networking". Image source: © C. Arnoldi

## 4.1. Product

The product to be manufactured is a personalized business card case. As shown in figure 4, the product consists of up to four components (base plate, holding spring, lid and inlay) and can be individualized in many ways. The engraving of the plexiglass base plate as well as the color and the laser engraving of the metal lid can be adapted individually to each customer.

Figure 4:
Personalized business card case (left) as product of the ***SmartFactory***KL pilot plant with individual components: base plate, holding spring, inlay and lid (right).

*Specification of the product*

| *Electromechanical specifications:* | |
|---|---|
| *Mechanism on reading and writing access to the digital product memory* | ***RFID tag (13.56 Mhz)***<br>• The RFID tag is firmly integrated into the master component of the product (base plate).<br>• The customer-individual product parameters are saved in the digital product memory during the intake of the orders. |

| *Information technology specifications:* | |
|---|---|
| *Information model of the digital product memory* | ***"SF information model for products – v1.0"***<br>• Information on order number, order date, production status, priority, productions steps, used energy per module, duration of the production steps, lid color, customer data for QR-code (laser engraving) and engraving bottom |

## 4.2. Production layer

To produce the individual business card case, up to nine different production modules are connected to a production process depending on demand. The following production modules are available: a pallet storage module, an engraving module, a laser-engraving module, a commissioning module, a handling module to insert the holding spring, a joining module for pressing the lid, a module for optical quality control, a weighing module and a replacement module to bridge individual process steps.

Figure 5:
The production process of the production of the business card case currently consists of nine different production modules.

## *Specification of the production modules*

### *Mechanic specifications:*

**Basic structure**

*"SF basic structure – v1.0"*

- Module measurements [m]: L 1.20xB 0.80xH < 1.90

**Transport system**

*"SF transport system – v1.0"*

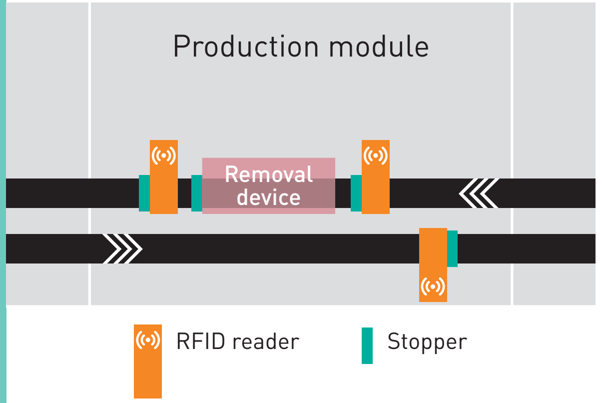
- Modular transport system with two revolving conveyor belts,
- locking devices and defined transfer points for the products:
  - » Open lock: passing on the product
  - » Closed lock: diverting of forwarding and returning belt

### *Electromechanical specifications:*

**Mechanism for reading out the digital product memory**

*"SF product tracking – v1.0"*

- 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.

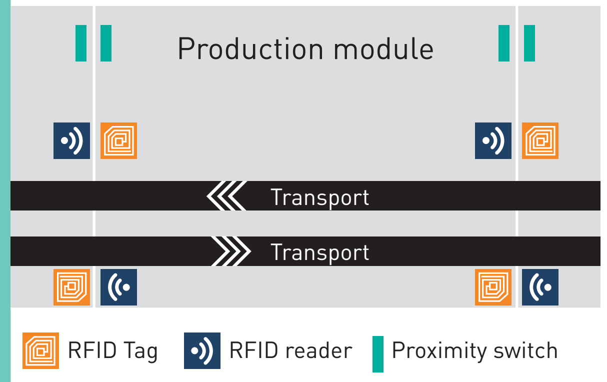



### *Electromechanical specifications:*

**Mechanism for recognizing the plant topology**

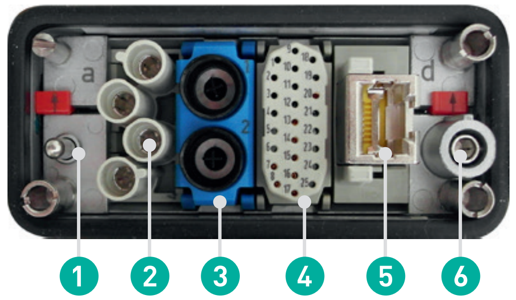
*"SF topology recongition – v1.0"*

- Assembly group of a RFID reader, RFID tag as well as two proximity switches for recognition and unique identification of the neighboring production module.




**Connection to the supply infrastructure**

*"SF modular socket – v1.0"*




1. Protective conductor
2. 400V three phased AC current
3. Compressed air
4. Safety function & 24V DC voltage
5. Industrial Ethernet
6. Protective conductor

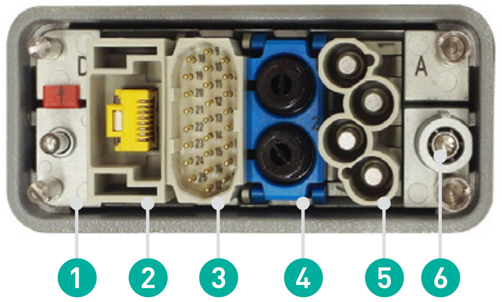
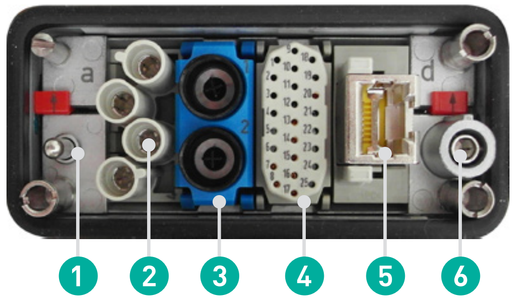
| Information technology specifications: | |
|---|---|
| *Information model of the production module* | ***"SF information model for production modules – v1.0"***<br>• Information on: properties, production status, operating status, topology (neighboring module) as well as resource demands and usage of the production module. |
| *Information model of the digital product memory* | ***"SF information model for products – v1.0"***<br>• cf. specification of the product |

| Standardized operating concept: | |
|---|---|
| *Operation states* | • Normal,<br>• Maintenance/setup<br>• Decommissioning |
| *Behavior states* | • Report<br>• Production<br>• Clear<br>• Transport<br>• Power down |

## 4.3. Supply layer

The supply layer enables a standardized connection and supply of the production modules. Currently, there are four manufacturer-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 module and enable the communication between the production layer and integration layer by means of Ethernet.

**Specification of the supply modules**

| Electromechanical specifications: | |
|---|---|
| *Connection to the production modules* | ***"SF modular plug – v1.0"***<br><br>1 Protective conductor<br>2 Industrial Ethernet<br>3 Safety function & 24V DC voltage<br>4 Compressed air<br>5 400V three phased AC current<br>6 Protective conductor<br><br>***"SF modular socket – v1.0"***<br><br>1 Protective conductor<br>2 400V three phased AC current<br>3 Compressed air<br>4 Safety function & 24V DC voltage<br>5 Industrial Ethernet<br>6 Protective conductor |

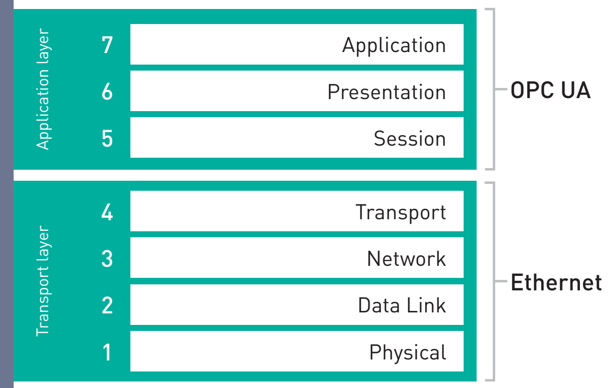
## *4.4. Integration layer*

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. 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*

| *Information technology specifications:* | |
|---|---|
| *Information model of the production module* | ***"SF information model for production module – v1.0"***<br>• cf. specification of the production module |
| *Information model of the digital product memory* | ***"SF information model for products – v1.0"***<br>• cf. specification of the product |
| *Communication protocol on reading/writing access from the production layer* | ***Communication protocols (in the OSI reference model):***<br>• Transport layer: Ethernet<br>• Application layer: OPC UA (IEC 62541) |
| *Communication protocol on reading/writing access from the IT layer* | ***Communication protocols:***<br>• Many communication protocols are possible, e.g. :<br>» MQTT<br>» RESTful WebService<br>» SOAP web service |



## *4.5. 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 analytics (Big Data) as well as remote monitoring/maintenance (cf. figure 6).

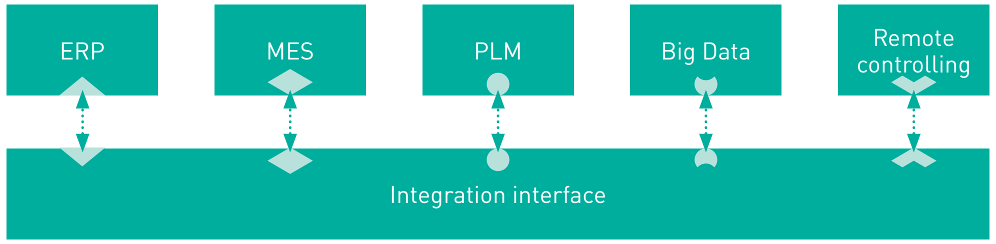



Figure 6:
Enclosure and connection of the IT systems as modular function components.

*Specification of the IT system interface*

| *Information technology specifications:* | |
|---|---|
| *Information model of the production module* | ***"SF information model for production module – v1"***<br>• cf. specification of the production module |
| *Information model of the digital product memory* | ***"SF information model for products – v1"***<br>• cf. specification of the product |
| *Communication protocol on reading and writing access* | ***Communication protocols:***<br>• cf. specification of the integration interface |

# *5. Classification of the system architecture in RAMI 4.0*

The ***SmartFactory***[KL] system architecture for Industrie 4.0 production plants can be appropriately imaged to the different dimensions of the Reference Architecture Model Industrie 4.0 (RAMI 4.0) of the Platform Industrie 4.0 (cf. figure 6).

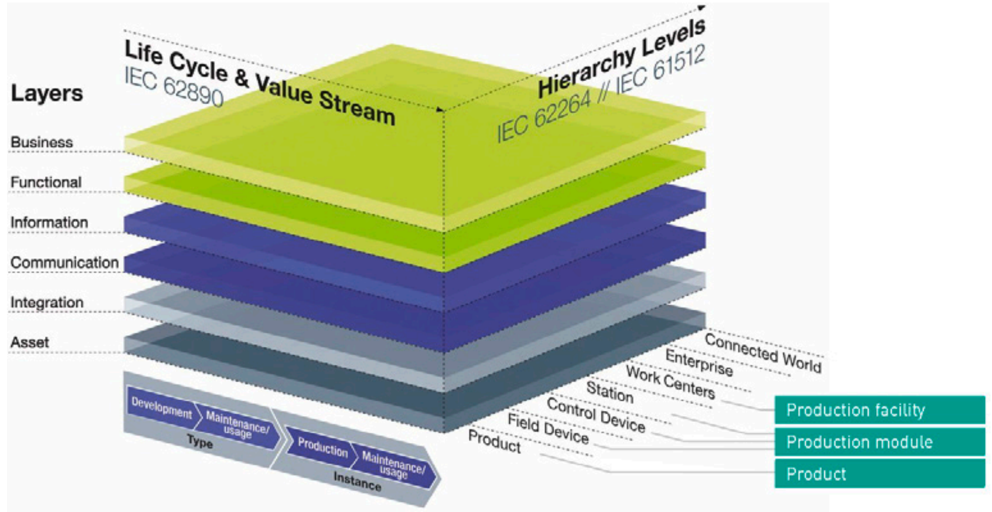



Figure 7:
The RAMI 4.0 - presented in the three-dimensional model - and the ***SmartFactory***[KL] system architecture for Industrie 4.0 production plants are compatible with each other.

Image source:
© Plattform Industrie 4.0

## *5.1. RAMI 4.0 hierarchy levels*

The hierarchy levels defined in RAMI 4.0 image the structural elements of a producing company (Enterprise). A company operates Work Centers, which consist of a chain of production modules (Station). The Work Centers are specified in their production capability by means of the manufactured Product.

Currently, the structural elements of control device and field device are not explicitly monitored in the ***SmartFactory***[KL] system architecture, but included as part of the production module.

## *5.2. RAMI 4.0 layers*

RAMI 4.0 defines 6 different layers which distinguish factory items regarding physical and information technology-related aspects. The RAMI 4.0 layers can be contrasted with the ***SmartFactory***KL system architecture, as shown in table 1.

| | *Layer* | | |
|---|---|---|---|
| ***Components*** | ***Asset*** | ***Information, Communication & Integration*** | ***Functional & Business*** |
| ***IT system layer*** | Cloud-based or local server infrastructure | IT system interface | Functionalities of computer-supported production planning, control and optimization. |
| ***Integration layer*** | Cloud-based or local server infrastructure | Integration interface | Functionality on logical data integration and persistent storage |
| ***Supply infrastructure layer*** | Supply module and cable | *(in progress)* | Functionalities on energy supply and monitoring, security functions |
| ***Production layer*** | Production modules | Auto ID concept, Information model of the production module | Functionalities on executing production, mounting, checking and handling processes |
| ***Product*** | Product | Auto ID concept, Information model of the digital product memory | Functionality of the product |

Table 1:
The 6 layers in the RAMI 4.0 are contrasted with the 5 components of the system architecture for Industrie 4.0 production plants.

## *5.3. RAMI 4.0 administration tray*

The information models defined in the ***SmartFactory***KL system architecture have their equivalent in the Administration Shell of the RAMI 4.0 (cf. figure 8).

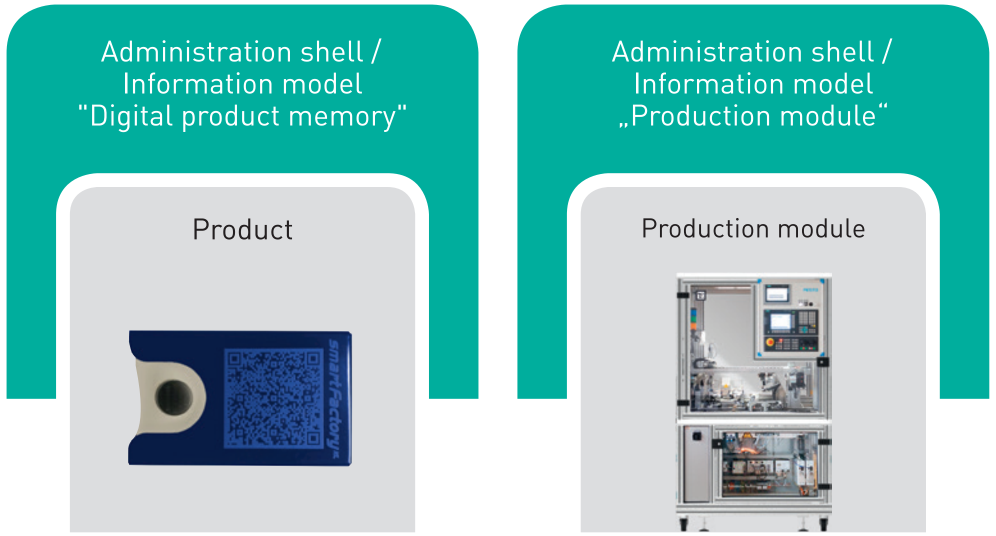



Figure 8:
Presentation of the information models in the concept of the Administration Shell.

# 6. Summary and outlook

## 6.1. Summary

This white paper describes a system architecture for Industrie 4.0 production plants, which was applied taking the example of the pilot plant of the ***SmartFactory***KL and was substantiated around cross-manufacturer specifications. It is the aspiration of the system architecture to show practical solution patterns on how modern production plants can be conceptualized, structured and operated in the discrete, loosely linked flow production.

The displayed specifications of the ***SmartFactory***KL pilot plant serves as orientation aid for the interpretation and conception of similar production plants, which are targeted towards mechatronic changeability, individualized mass production and internal and cross-company networking.

The classification of the system architecture into the Reference Architecture Model Industrie 4.0 (RAMI 4.0) of the Platform Industrie 4.0 shows the compatibility and openness in comparison with complementary approaches and concepts in the range of Industrie 4.0.

## 6.2. Outlook

The system architecture in general and the specifications of the pilot plant in particular are continuously refined regarding their practicality within the work groups[6] of the ***SmartFactory***KL.

- From the prototypical realization to industrial practice: Even though the technical feasibility as well as the expected technological advantages of the system architecture could be confirmed, the application of the system architecture in the broad industrial practice is still missing. For a successful transfer, the consideration of security-relevant regulations and the availability of market-ready solution components are especially essential.

- Fine-tuning the ***SmartFactory***KL system architecture: A fine-tuning of the ***SmartFactory***KL system architecture regarding further hierarchy levels is being planned. With this, the further modular decomposition and structuring of production modules into smart field devices (cyber-physical systems) is possible – enabling an extended mechatronic changeability.

Development of further information models: The modelling and application of information models are crucial in closing the gap between the physical and digital world. Currently, further information models are being planned. An information model for the supply modules (1) is supposed to enable the automatic recognition of the supply topology and another for the production plant (2) is supposed to image the abilities and properties of the modular overall plant setup.

6 The ***SmartFactory***KL network is organized in four work groups, which create the basis for the practical implementation of intelligent production concepts. The work groups meet regularly in order to develop common specifications and standards, which correspond with the ***SmartFactory***KL vision. Many results are directly transferred into the development and the operation of prototypes in order to collect practical experience, which will then in return be incorporated into the work of the work groups.

**Version history:**
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The technology initiative SmartFactory KL e. V. (***SmartFactory***KL) is a non-profit association under public law registered at the association register Kaiserslautern.

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