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*industrie 4.0, internet-of-things,*
*cyber-physical systems, industrial product-service systems,*
*condition monitoring, predictive maintenance*

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# INTELLIGENT PRODUCTION SYSTEMS IN THE ERA OF *INDUSTRIE 4.0* – CHANGING MINDSETS AND BUSINESS MODELS

*Industrie 4.0* has been becoming one of the most challenging topic areas in industrial production engineering within the last decade. The increasing and comprehensive digitization of industrial production processes allows the introduction of innovative data-driven business models using cyber-physical systems (CPS) and Internet of Things (IoT). Efficient and flexible manufacturing of goods assumes that all involved production systems are capable of fulfilling all necessary machining operations in the desired quality. To ensure this, production systems must be able to communicate and interact with machines and humans in a distributed environment, to monitor the wear condition of functionally relevant components, and to self-adapt their behaviour to a given situation. This article gives an overview about the historical development of intelligent production systems in the context of value-adding business models. The focus is on condition monitoring and predictive maintenance in an availability oriented business model. Technical as well as organizational prerequisites for an implementation in the production industry are critically analysed and discussed on the basis of best practice examples. The paper concludes with a summary and an outlook on future research topics that should be addressed.

## 1. INTRODUCTION

### 1.1. INTELLIGENT PRODUCTION SYSTEMS

Numerous definitions of machine intelligence exist in literature. Legg and Hutter propose in [1] the following informal definition of machine intelligence: "*Intelligence measures an agent's ability to achieve goals in a wide range of environments*". In the present paper it is suggested for common understanding to characterize an intelligent production system by its cognitive ability which is a fundamental requirement for efficient interaction in a distributed industrial production environment, where humans and objects collaborate in complex processes along the entire value-creation chain. Table 1 shows which

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level of intelligence can be reached by enabling technologies commonly used in the production industry while Fig. 1 depicts the principle architecture of a cyber-physical system that includes all features to realise an Intelligent Production System.

Table 1. Enabling technologies for Intelligent Production Systems

| Enabling Technology | Features | Application | Level of Intelligence |
|---|---|---|---|
| Barcode (1D)<br>QR ( Quick Response code ) (2D) | • Optically stored information<br>• Passive communication<br>• Read-only<br>• Optical path | • Identification | • No cognitive ability<br>• Passive information provision |
| RFID ( Radio-frequency identification) | • Electronically stored information<br>• Passive or active communication<br>• Read/write<br>• Radio transmission | • Identification<br>• Tracking and Tracing<br>• Documentation | • No cognitive ability<br>• Active information provision |
| Wireless sensor node | • Electronically stored information<br>• Active communication<br>• Data processing<br>• Radio transmission | • Identification<br>• Tracking and Tracing<br>• Documentation<br>• Monitoring and Control<br>• Interaction | • Cognitive ability<br>• Collaboration |

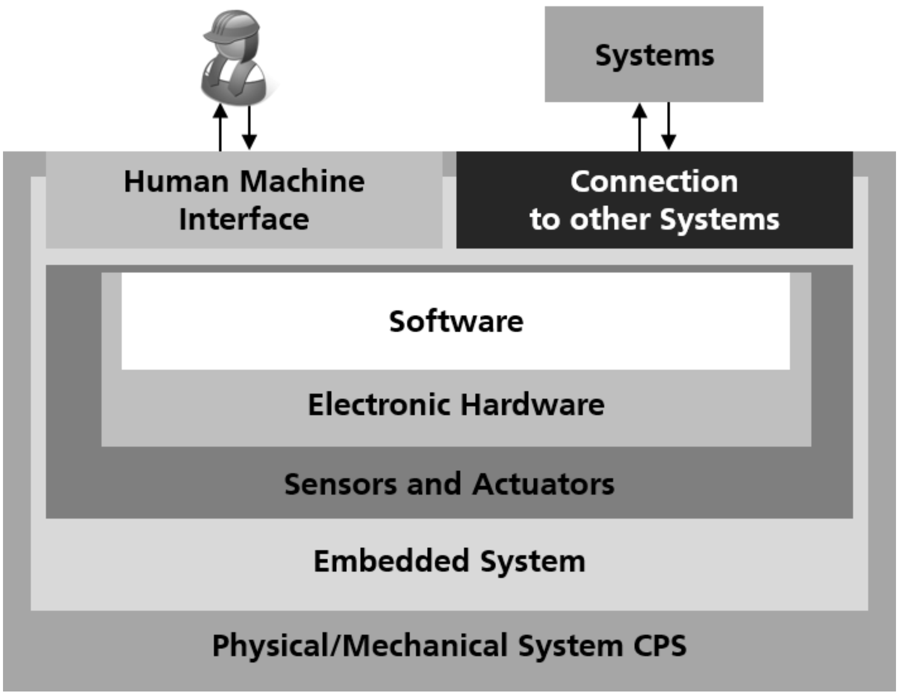


Fig. 1. Onion architecture of an Intelligent Production System (based on [2])

### 1.2. DEVELOPMENT STEPS OF INTELLIGENT PRODUCTION SYSTEMS

The request for efficient manufacturing provoked the so called industrialization which first has started in England in the 18th century. In 1776 James Watt and Matthew Boulton began to lease their steam engines instead of selling them to mine owners. Their business model was to lease their product for a third of what it costs them to feed their workhorses in a defined time period. To proof how much workhorse power was saved by a steam engine it became necessary to monitor the performance during the use phase. For this reason Watts developed a mechanism to count the number of working strokes. This mechanical counter was installed in the steam engine and could only be accessed by authorized persons. In a certain sense this kind of steam engine can be seen as a very simple intelligent production system due to its ability to monitor its performance and to communicate the stored result to a human.

Besides the use of energy-driven machines that were able to take on tasks formerly performed completely by human, the possibility of sequential division of labour leaded to the first assembly lines where the parts moved automatically from workstation to workstation. This kind of a sequential rigid chained production process needs to be monitored and controlled by a control system. The main control system of Henry Ford's assembly line in 1913 was a conveyor belt that allowed the optimization of interoperability by adapting its speed.

The application of electronic devices in the 1950s and information technology in the late 1960s for automation allowed the implementation of computer programs to run on production systems and therewith to adapt the behaviour to given input parameters in an intelligent but more or less encapsulated way.

With the advent of the information and communication technologies (ICT) in the 1970s and 1980s the concept of computer integrated manufacturing (CIM) was established. The concept stands for the comprehensive implementation of ICT along the entire value-creation-chain in industrial production as a basis for continuous data flow from product design and job order to production facilities. Due to the fact that the core technologies used for *Industrie 4.0* are still the same but optimized in speed, performance and physical size, *Industrie 4.0* can be seen, from a technological point of view, more as industrial evolution instead of a revolution.

## 2. *INDUSTRIE 4.0*

### 2.1. THE IDEA OF *INDUSTRIE 4.0*

The term *Industrie 4.0* (The German designation *Industrie 4.0* instead of industry 4.0 which is used by some other authors for the same meaning is preferred in this keynote to highlight that it is a brand label) was officially presented to the public for the first time by Kagermann, Lukas and Wahlster at the Hanover Fair 2011. It stands for a paradigm shift in the industry and is Germany's ambition towards the so called fourth industrial revolution [3]. Today, there are more than 100 characterizations and definitions for *Industrie 4.0* varying in terms of goal and focus. A clear and commonly accepted definition of *Industrie 4.0* does not yet exist. The analysis of hits for the keywords "*Industrie 4.0*" OR "Industry 4.0", "Internet of things" OR "Internet-of-things" OR "IoT" and "cyber-physical system" on the online database ScienceDirect (http://www.sciencedirect.com/) confirms the results of Monostori et al. presented in [4]. Since the term *Industrie 4.0* was coined in 2011, a rapid increase of scientific papers related to this topic can be noted and it is expected that this trend will go on for the next years (see Fig. 2).

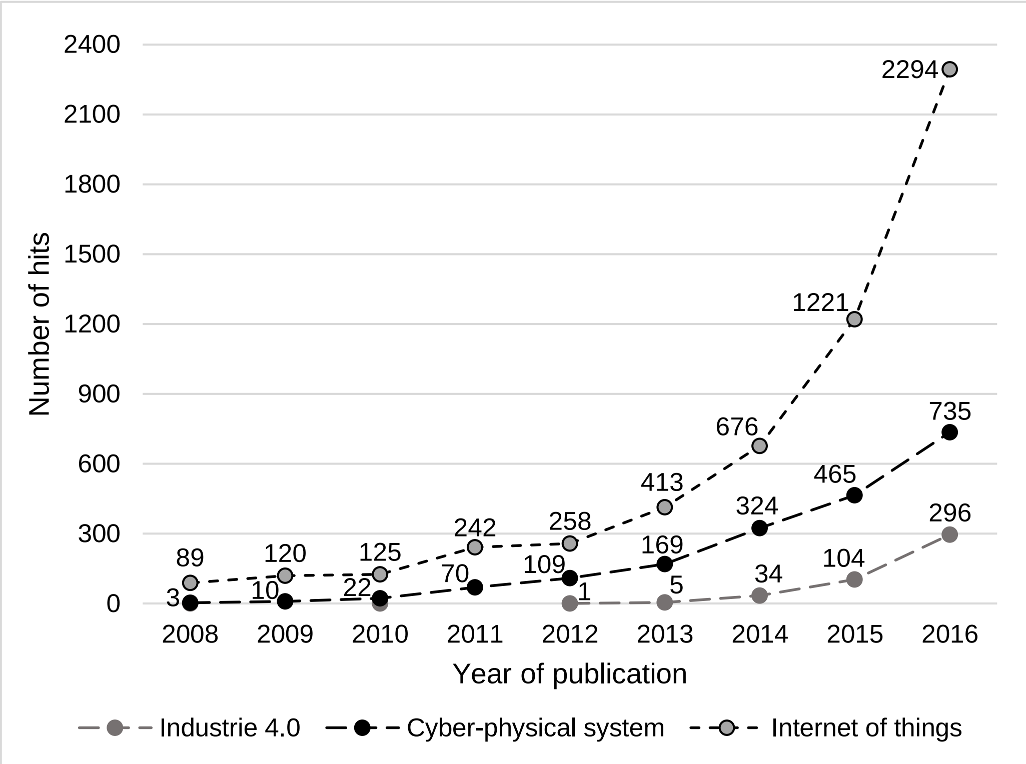


Fig. 2. Results of the analysis of *Industrie 4.0* related keywords on Elsevier website ScienceDirect

The "Plattform *Industrie 4.0*" is a joint project of the three German trade associations the German Federal Association for Information Technology, Telecommunications and New Media BITKOM, the German Engineering Federation VDMA and the German Electrical and Electronic Manufacturers' Association ZVEI. They define *Industrie 4.0* as follows:

"*The term Industrie 4.0 stands for the fourth industrial revolution, the next stage in the organisation and control of the entire value stream along the life cycle of a product. This cycle is based on increasingly individualised customer wishes and ranges from the idea, the order, development, production, and delivery to the end customer through to recycling and related services. Fundamental here is the availability of all relevant information in real-time through the networking of all instances involved in value creation as well as the ability to derive the best possible value stream from data at all times.*

*Connecting people, objects and systems leads to the creation of dynamic, self-organised, cross-organisational, real-time optimised value networks, which can be optimised according to a range of criteria such as costs, availability and consumption of resources.*”

The basic idea of *Industrie 4.0* is the implementation and use of the internet of things technologies, services, processes and especially people, a challenge which is not solved when it comes to the question of digital consistency in engineering. Ubiquitous, surrounding networking of people, machines, objects and IT-systems will enable horizontal integration in value added networks and will break with the strict separation of the established levels of the automation pyramid. Manufacturing intelligence and functions will more or less change from centralization to decentralization, and this also calls for a new design of the sociotechnical system. For this reason *Industrie 4.0* applications combine different technologies from the wide field of digitization to realize the above mentioned goal to optimize the value stream in industrial production. Fig. 3 gives an overview of technologies suitable for *Industrie 4.0* and their possible application fields.

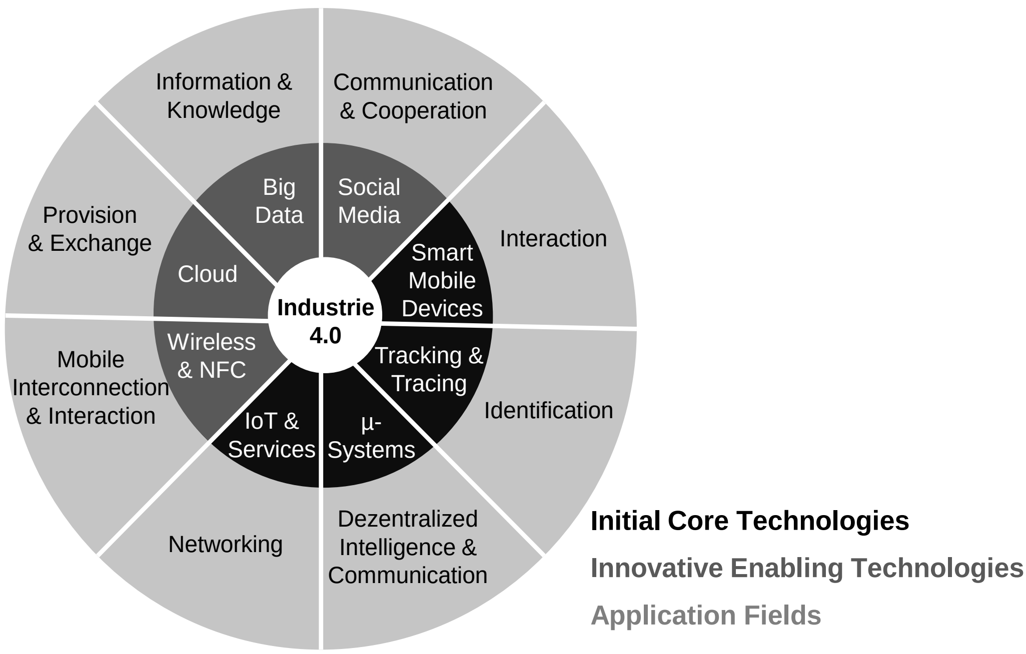


Fig. 3. Technologies and their application fields of *Industrie 4.0*

Regarding the commonly accepted first three industrial revolutions, characterized by mechanization, electrification and use of electronics and information technology, it can be stated that they were driven by the early adoption of emerging technologies for industrial production purposes. From the technological point of view, the term *Industrie 4.0* denotes an evolutionary phases of the third industrial revolution due to the fact that the fundamental enabling information and communication technologies have been used in industry since the era of Computer Integrated Manufacturing (CIM) [5]. It describes a new phase of organization and control of the entire value chain over the life-cycle of products. Fig. 4 depicts the steps of development towards *Industrie 4.0*.

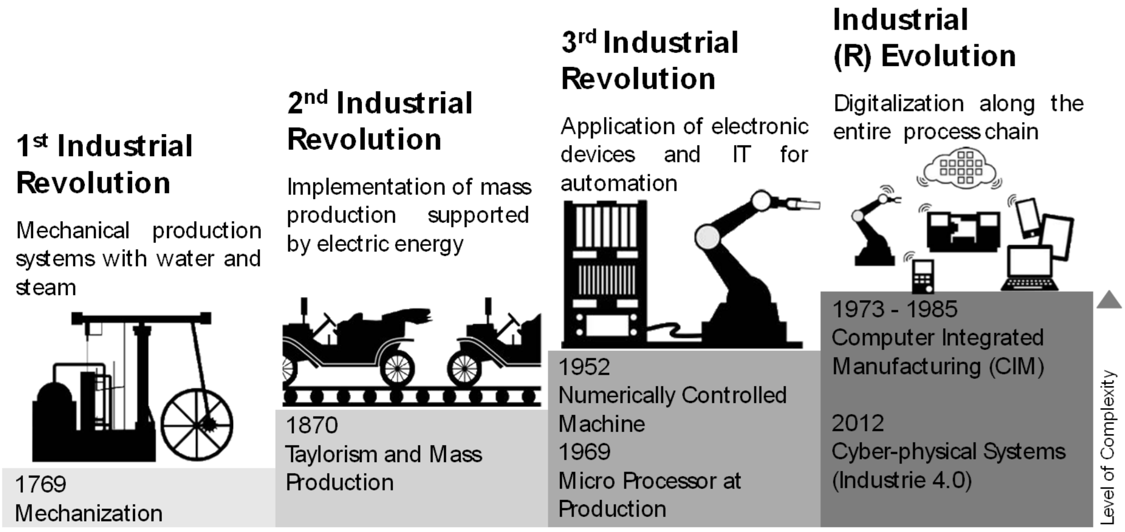


Fig. 4. The four steps of industrialization (based on [6])

*Industrie 4.0* offers the opportunity of implementing innovative data-driven business models like "Pay per X" which means that the customer only pays for the actual benefit and not for the production system itself. The basis of such business models are cyber-physical systems as data sources, the data itself, cloud platforms to provide services and the real services, e. g. predictive maintenance, process optimization or energy management. In this way the role of manufacturers will change from manufacturing service providers to service providing manufacturers.

## 2.2. INTERNATIONAL RESEARCH PROGRAMS

The trend towards digitally integrated production leads to a worldwide paradigm change with different country specific objectives. The United States of America want to bring digital innovations to the physical world in order to recover its industry to have a renaissance of production. The most active group in the USA are the start-ups for internet of things. The ability to scale up smart factories and large manufacturer is the driver for Japan and South Korea. The way of China is characterized by speeding up the economy and by pragmatic applications for quick wins combined with the development of long-term strategies. At European level the European Community implemented the Horizon 2020 program for the generation of growth and jobs through research and innovation. Horizon 2020 is subdivided in three main research areas. The research area "Industrial Leadership" aims at bringing Europe in a leading role of industry in manufacturing, processing and ICT. From 2014 to 2020 the European Community provides about 14 Billion € subsidies for projects in this topic area. Germany is striving for engineering excellence with visionary concepts for technology, society and economy integration. Within the German government's Hightech Strategy the Federal Ministry for Education and Research (BMBF) started in 2011 the future project *Industrie 4.0* with the aim to establish Germany as pioneer regarding the solution of global challenges of industrial production. Focus lays on production and ICT research for an intelligent interconnection in production. Between 2011 and 2017 63 projects are funded by subsidies at an amount of 46.1 Million €. The German Federal Ministry of Economics and Technology (BMWi) funds 14 projects with 39.1 Million € in its program AUTONOMIK for *Industrie 4.0* between 2014 and 2017. The program aims at interlocking information and communication technologies (ICT) with industrial production to exploit innovation potentials and accelerate the development of products.

## 3. INTELLIGENT SYSTEMS IN RESEARCH

### 3.1. INTERNATIONAL RESEARCH

Research on the use of control internal data of production machines for process and condition monitoring already started in the 1990s [7-8]. Byrne et al. concluded in [9] that "*... the sensor and sensor system must become integrated as part of the 'intelligent machine tool'. ...*". Research in the production industry aimed at generating more knowledge from machine and process data by the adoption of machine learning methods [10-11] and researchers began to connect production machines directly to the internet for the purpose of providing innovative services often related to the goal of maximizing the technical availability [12]. These activities led in the early 2000s to the development of web-based platforms for the provision of manifold services for the manufacturing industry. A common feature of those platform approaches is that data acquired at the production system is used for data-driven service provision which is also a goal of *Industrie 4.0*.

The concept of the "Watchdog Agent™" was developed at the NSF Industry/University Cooperative Research Center on Intelligent Maintenance Systems (IMS). The concept allows web-enabled monitoring and prognostics for different application fields including manufacturing. Nevertheless, a Watchdog Agent has not necessarily to be integrated in a web-service architecture. It is also possible to run it as standalone application which is embedded in the system to be observed [13].

Within the Fraunhofer internal research project "e-Industrial Services" focused on web-based value-added services for the producing sector in the areas of "e-Learning", "e-Logistics" and "e-Maintenance". The area of e-Maintenance included beside others services for condition monitoring and predictive maintenance using enhanced diagnostic algorithms. A prerequisite for these services was to enable machine tools to perform self-tests, to acquire control internal data like drive signals, machine parameters and system messages and to communicate with web-services for data analytics [14]. In contrast to the IMS approach the task of complex data analytics is shifted from local to a powerful web-server. Fig. 5 shows the implemented client server architecture for condition monitoring as an e-Industrial Service.

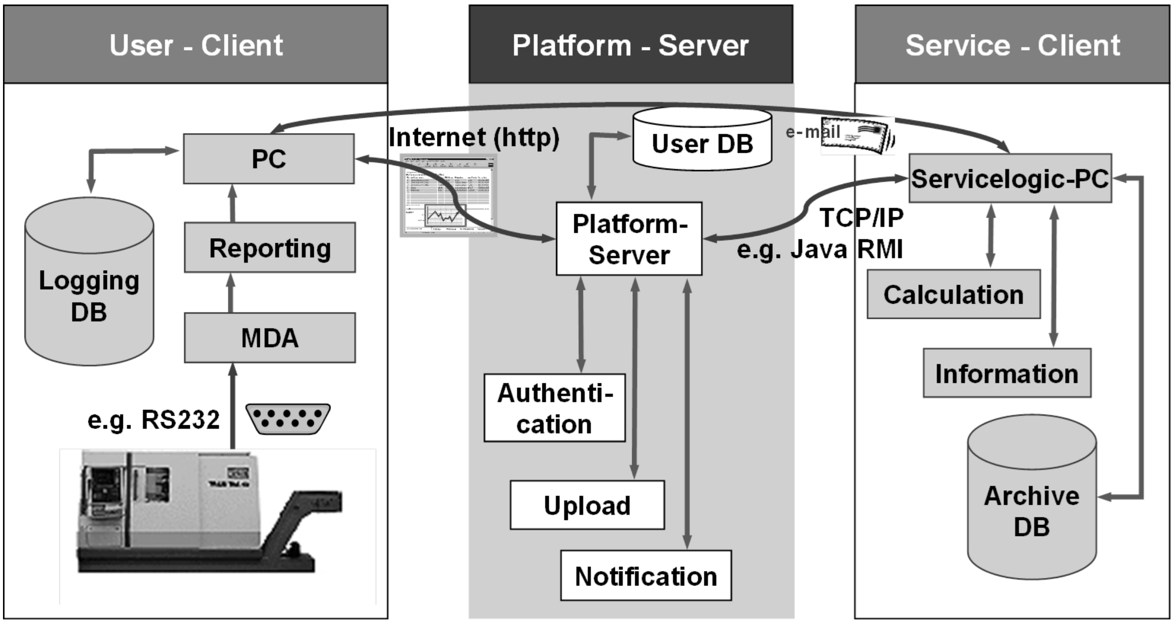


Fig. 5. Client server architecture for condition monitoring as e-Industrial Service [14]

Around the same time, several further research and development projects with focus on internet based services have been realized. One example is the joint project "Embedded Online Services (EOS)" in which a reference architecture for teleservices for the manufacturing industry was developed by a consortium of research and industrial partners. Services like "software update", "training" and "remote diagnosis" were exemplarily implemented [15]. An example for an industrial solution are the ePS Network Services developed by Siemens. The ePS Network Services are based on data acquired from the Siemens control system SINUMERIK 840D. Data is uploaded to a service platform where it is processed, visualized and provided via internet access [16]. In the meanwhile, the ePS Network Services were expanded and the brand was changed to "SINUMERIK Integrate". Services provided by this internet platform are called "Access MyPerformance", "Manage MyProgramms", "Manage MyTools" and "Analyze MyCondition" [17].

As Djurdjanovic et al. state in [13] even in this time production machines were "... *actually quite 'smart' in themselves* ..." by having the ability to provide data about the machine's health status and performance. They further state that only "... *little or no practical use is made of most of this data* ..." due to inappropriate data formats and absence of infrastructure to realize "… *a continuous and seamless flow of information throughout entire processes*."

As a consequence of the idea of providing value-added services in the production sector the innovative paradigm of Industrial Product-Service Systems (IPS²) became established in academic circles with the foundation of the CIRP Working Group IPS² in the year 2007. Since 2009 the CIRP sponsored International Conference on Industrial Product-Service Systems takes place annually at different locations. Meier et al. define in [18] the concept of Industrial Product-Service Systems in the following way: "… *An industrial product-service system (IPS²) is characterized by the integrated and mutually determined planning, development, provision, and use of products and services* *including immanent software. IPS² are offered in business-to-business markets; they address industrial applications only. An IPS² represents a knowledge-intensive socio-technical system (Meier et al. 2010). …*”.

Research on IPS² focusses on an integrated view on products and services for industrial applications. One key aspect is the shift of responsibilities between manufacturers of production systems and their customers within innovative business models. They can be divided in functional, availability, and result oriented business models that focus consequently on the individual customer benefit. While in a function oriented business model the functionality of a production system can be provided by a maintenance contract, the availability oriented business model guarantees the usability of the production system is guaranteed by the IPS² provider. In such a business model the provider takes over the responsibility for business processes of the customer, e.g. implementation of predictive maintenance. Fig. 6 depicts the specifications of the three IPS² business models [19].

| | Function oriented | Availability oriented | Result oriented |
|---|---|---|---|
| Production responsibility | Customer | Customer | Provider |
| Supply of operating personnel | Customer | Customer | Provider |
| Service initiative | Customer | Provider | Provider |
| Supply of maintenance personnel | Customer/ Provider | Provider | Provider |
| Turn over model | Pay on service order | Pay on availability | Pay on production |

Fig. 6. Specification of innovative IPS² business models (following [19])

Especially the implementation of an availability oriented business model requires the existence of intelligent production systems that are able to monitor their health status, adjust their performance and communicate and interact with the manufacturer as service provider to ensure the system’s technical availability [20-23].

In the last few years the term “Digital Twin” has become very popular in industry [24-26]. Referring to Grieves and Vickers in [27] the origin of the Digital Twin concept is from the year 2001 and was presented to industry in 2002 by Grieves under the title “Conceptual Ideal for PLM” in the context of Product Lifecycle Management. Grieves defines the Digital Twin as “… *a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin. …*”.

As a Digital Twin is an exact virtual representation of a real physical system it contains all digitized information along the system's life-cycle, from the early development stage to its use phase. In combination with environmental data the Digital Twin can be used to predict the future performance and behaviour of the real system. Generating a digital model from the micro atomic level to the macro geometrical level of a physical product is nowadays still challenging due to the multi-domain modelling task. Nevertheless, partial models for specific purposes, e.g. for simulating kinematic or process behaviour as well as for wear and tear prediction exist already.

### 3.2. RESEARCH FOR A DIGITIZED PRODUCTION AT FRAUNHOFER IPK

The roadmap towards intelligent production systems and therewith towards *Industrie 4.0* at Fraunhofer IPK started in the 1990s with the connection of CNC machine tools to the internet for remote monitoring and control purposes. Control internal data was sent to a server via TCP/IP, used and visualized in a virtual man machine control and also used to animate a virtual representation of the real machine tool. In the opposite direction it was possible to change machine parameters or to send control commands that were executed by the machine's control system. In the early 2000s the Fraunhofer Group for Production set up an internal research project to develop internet-based industrial services. In times where manufacturers of machine tools had only week internet presence Fraunhofer developed a service platform tailored for the needs of machinery and plant manufacturing. This platform offered several basic services like session logging, authentication and authorization as well as up- and downloading of data and messaging. Furthermore value-added services for the producing sector have been developed. One focus was on the support of maintenance to increase the technical availability of production systems. Drive data of feed axes acquired during the execution of self-tests, was uploaded to the server and analysed by a condition monitoring web service. To access the load history of a machine tool further control internal data like operating hours and the overall travelled distance of feed axes was continuously logged and used for condition based maintenance planning also. After the implementation of parts of the concept in real industrial environments, it became obvious that condition monitoring data provides much more potential for value-added services if it is enriched with additional information about the history of product configuration and service activities, e.g. from Product Data Management, Enterprise Resource Planning and Maintenance Management. With these interlinking of data from different phases in the life cycle of a production system for monitoring purposes the concept can be extended to a so called Life-Cycle Monitoring System (see Fig. 7).

Further research activities addressed the direct support of service technicians during interaction with machine tools. A concept for a mobile service support system based on modelled service processes using the method of business process modelling was developed. The concept includes a graphical user interface (GUI) for context-related interactive instructions. Depending on the results of self-tests triggered by remote procedure calls from the GUI, the adequate instruction is presented to the Service technician.

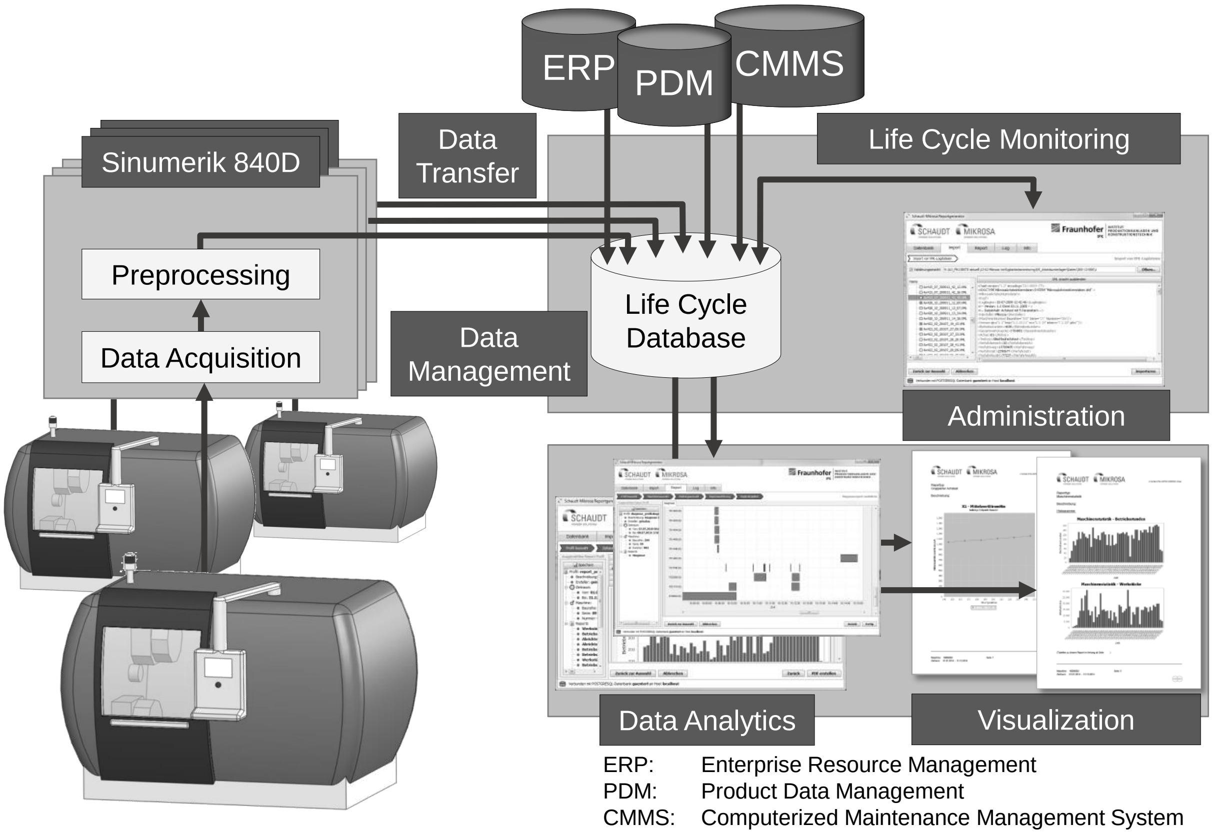


Fig. 7. Global Structure of a Life Cycle Monitoring System (following [28])

Currently, more than 10 different research projects in the context of *Industrie 4.0* are performed at Fraunhofer IPK. Four projects with strong relations to intelligent production systems funded by the German Federal Ministry of Education and Research (BMBF) are described in more detail in the following sections.

## Industry Cockpit

Transparency of production processes is the most important prerequisite for flexible production networks. To ensure that all stakeholders keep track of what is happening, together with an industrial partner Fraunhofer IPK developed a concept for a dynamic control centre to monitor and control flexible manufacturing networks. The proposed concept provides methods for process monitoring at the management level as well as for deriving real-time information at the operational level, where the system automatically documents the progress of the job process and provides the information that is relevant to respective staff members. The industry cockpit works on the basis of process models where all relevant information for process monitoring and tracking is linked together (cf. Fig. 8). It enables automated generation of individual dashboards from the available data and allows all involved stakeholders to monitor and control the job process. The data needed for this model based process monitoring and control is provided by humans as well as by intelligent production machines [29].

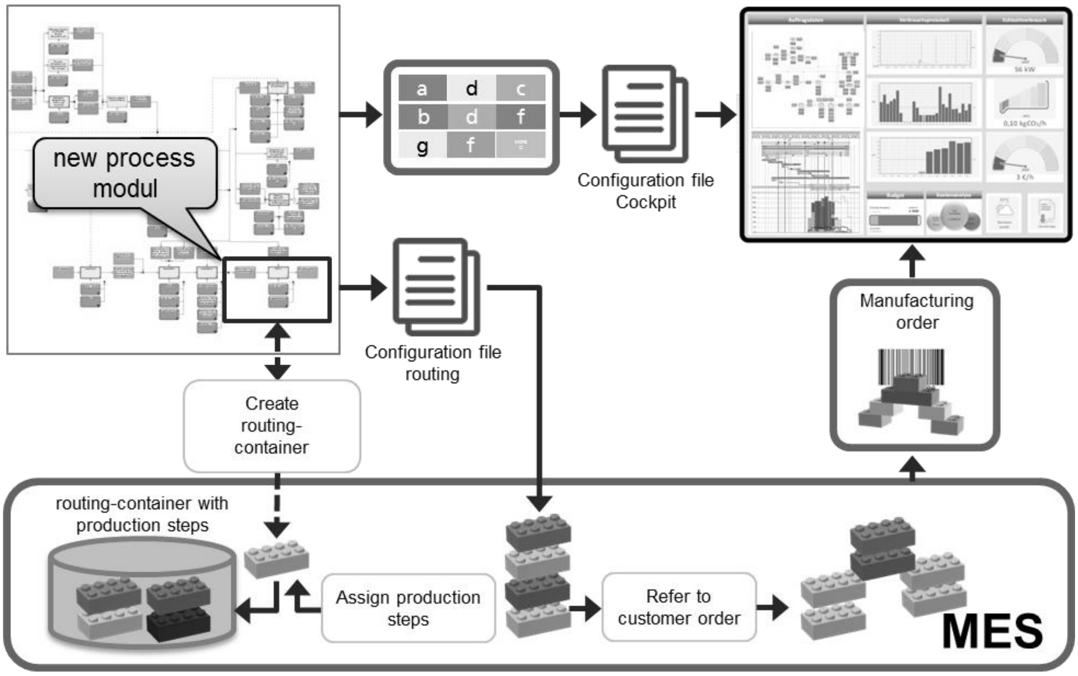


Fig. 8. Use Case implementation of the Industry Cockpit [29]

## Intelligent Self-organizing Workshop Production

The project Intelligent Self-organizing Workshop Production (iWePro) aims at planning and situation depending directing of job schedules to ensure a flexible and efficient production. State of the art in production planning is to plan production flows using machine allocation schedules in a way that allows production orders to be carried out cost-effectively and in accordance with given requirements. If adjustments during production become necessary, for example due to machine failure or changes in order prioritization, time-consuming manual rescheduling has to be done. The idea of iWePro is to enable production processes to be flexible structured on the basis of the job shop production principle. To realize this idea, iWePro uses a software agent-based assistance system that dynamically adjusts initially planned machine allocation. If adjustment becomes necessary the system assists at calculating alternative schedules and simulates them. The basis of this concept is the use of networked technologies for the communication between intelligent production systems, work pieces and staff. For this reason intelligent production systems need the ability to analyse their own states, anticipate maintenance requirements and report capacities [30].

## Industrial Cloud-based Control Platform for a CPS-based Production

Today’s automation of robots and machine tools is realized by on-site monolithic control systems that are directly connected to the respective production system. The aim of the joint research project Industrial Cloud-based control platform for a CPS-based

Production (piCASSO) is to substitute this traditional control concept by the development of a cloud-based scalable control platform. To do this, control functionality is modularized and extended to cloud-computing mechanisms (see Fig. 9), e.g. centralized data processing.

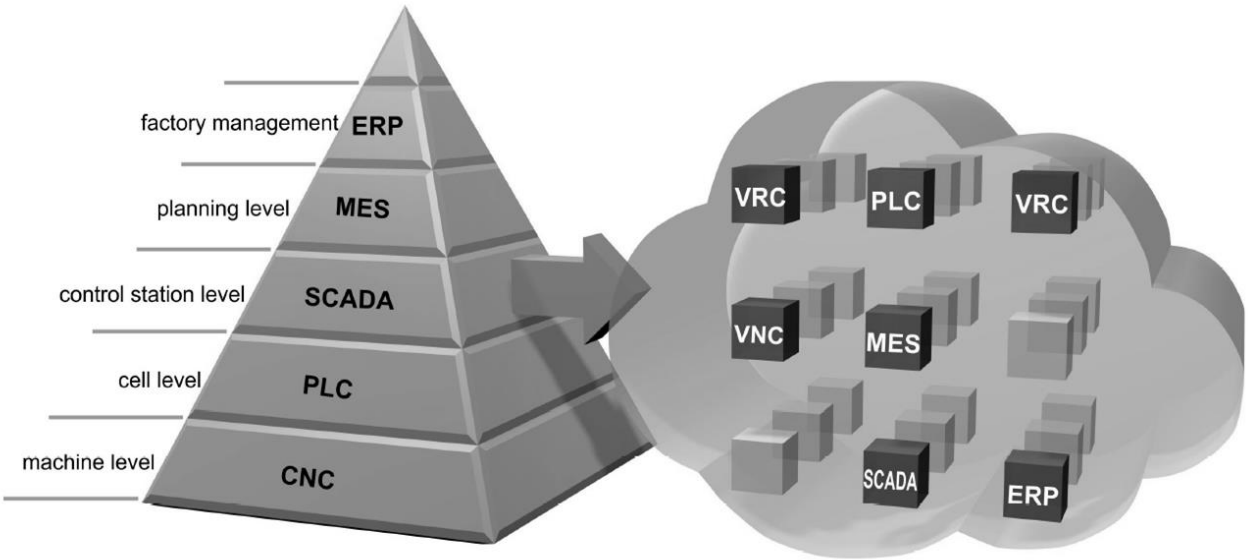


Fig. 9. Modularization and virtualization of factory control components [31]

Hardware-independent services running in the cloud allow a fast reconfiguration of control modules and the provision of numerous value-added service for increased production efficiency [31-32].

## MEMS-based Condition Monitoring

While modern production machines may have some integrated functionality to monitor their wear and tear condition, most of older existing machines do not have this ability. Furthermore, normally it is a complex undertaking to retrospectively implement such control integrated functionality due to missing access to and lack of know-how about the control. Furthermore, often additional and cost-intensive industrial sensors need to be implemented for a condition monitoring system. The project A Micro-electromechanical Electronic System for Condition Monitoring in *Industrie 4.0* (AMELI 4.0) addresses this challenge by developing sensor hardware, communication and analytics software. The system will allow an easy retrofitting of existing production machines and provides connectivity to *Industrie 4.0* topologies. The project's approach is the implementation of highly integrated, networked, energy self-sufficient MEMS multi-sensor systems with intelligent real-time processing of data on the sensor level and high data and system security. A key element of AMELI 4.0 is the development of adaptive, robust and intelligent analysis methods as well as self-learning algorithms for condition and process monitoring in a wide spectrum of industrial applications. This involves the development of a suitable IT infrastructure for data management of distributed data from multiple MEMS sensors and its implementation on individual sensor systems and in a gateway [33]. Fig. 10 shows the basic concept of AMELI 4.0.

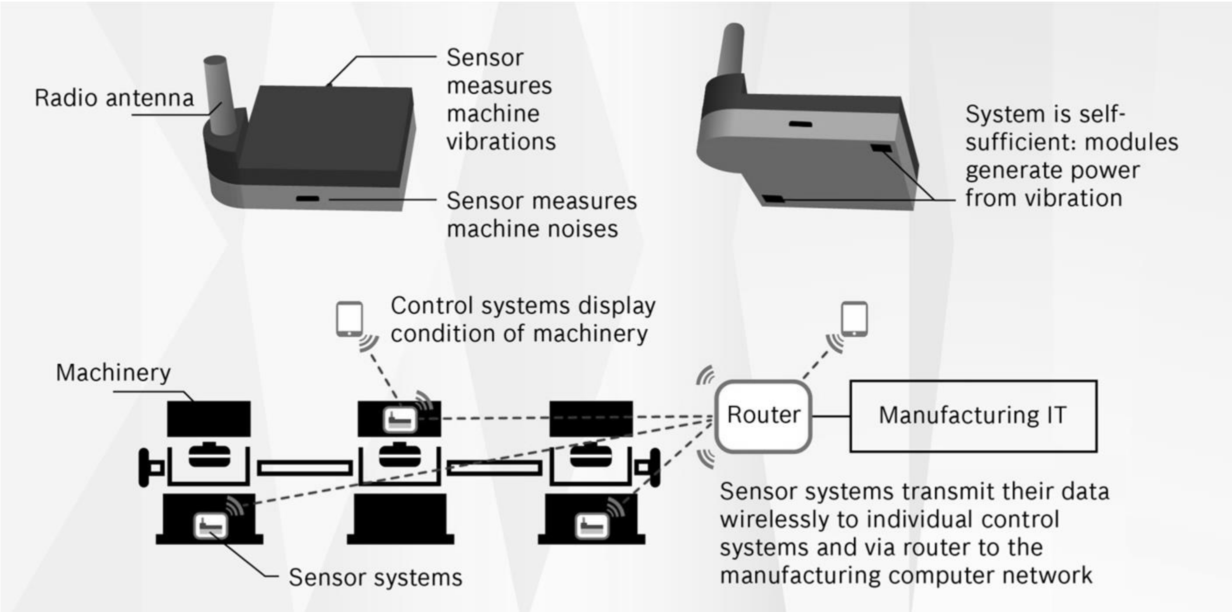


Fig. 10. AMELI 4.0 concept [33]

## 4. INDUSTRIAL APPLICATIONS

Along with the manifestation of the idea of *Industrie 4.0* and the increasing widespread availability of technologies and systems first commercial solutions for industrial implementation are on the market. In the following section some current examples are described.

### Monorail Guidance Systems 4.0

The Schaeffler Group presented 2015 in Milan, Italy at the Exposition Mondiale de la Machine Outil (EMO), a European trade show for the international manufacturing industries, an innovative monorail guidance systems as a machine component for an *Industrie 4.0* solution to the public. The system is equipped with piezoelectric vibration sensors for lubrication and bearing condition monitoring. The system is able to give direct feedback by on-board monitoring of limit values, but it is can also communicate with the machine's control unit to trigger lubrication and maintenance [34].

### Smart Sensor for Low Voltage Motors

A prototype of a smart sensor for condition monitoring of low voltage motors was presented from ABB Ltd. In Hannover, Germany at Hannover Messe 2016. The sensor measures key motor parameters such as vibration, temperature and others in intervals, at regular time intervals, processes them with on-board algorithms and transmits them wireless to a cloud-based. When a problem is detected an alert is sent to the operator of the motor. It is possible to apply the smart sensor box not only to new but also to already installed motors. ABB calculates that with the smart sensor it will be possible to reduce motor downtime by up to 70%, to extend motor lifetime by around 30% and to lower power consumption by up to 10%. ABB announces the commercial availability of the product at end of 2016 in the United States and in 2017 in other regions [35].

### Smart Seals

Freudenberg Sealing Technologies is investigating in how materials for sealing components can be transformed into sensors to make seals smart. Freudenberg aims at developing seals that are not only able to prevent material transfer but are able to monitor their own wear and tear. Further researching is done by Freudenberg to find out how the functionality of other dynamic sealing elements like diaphragms and U-rings can be extended by the use of dielectric elastomers [36].

### Intelligent Spindles

Cao et al. propose in [37] an integrated concept for intelligent spindles and provide a comprehensive overview about past and current research activities on intelligent spindles in the manufacturing industry. They note that research on intelligent spindles has been ongoing for about ten years but nevertheless there is still no known intelligent spindle in practical use in industry. *Industrie 4.0* related technologies like smart sensors and actuators and decentralized data processing and decision making in a Big Data environment will promote the development of intelligent spindles and their deployment in production industry.

### Single Board Computers for Cyber-Physical Systems in *Industrie 4.0*

Single board computers are currently subject of innovative approaches transform simple production systems into cyber-physical systems. Such computers equipped with sensors and attached to existing production systems can be used to enable them for interacting with the industrial production environment and for communicating with cloud services using IoT technologies. It depends on the application which degree of intelligence is needed. In its simplest form, system’s intelligence consists only in the ability of data acquisition and transfer is implemented while higher levels of intelligence require abilities like embedded data analysis and context-sensitive reaction, e. g. to avoid machine breakdown.

While researchers and developers still often single board computers systems like Raspberry Pi or Arduino for proofs of concept or the development of prototypes [38], there are already industrial-suited solutions on the market. Fig. 11 shows the communication architecture implemented at Fraunhofer IPK for condition monitoring in the cloud.

At the Hannover Messe 2016, the HARTING Technology Group presented a modular software and hardware platform for industrial digitization called MICA (Modular Industry Computing Architecture). The basis of MICA is a robust single board computer adaptable to many industrial applications using MQTT and OPC-UA protocols for communication. It can be directly integrated in the machine and process the acquired data onsite. MICA is also able to handle Big Data by using Hadoop and provides application programming interfaces for java, R, python, MySQL and C/C++ [39].

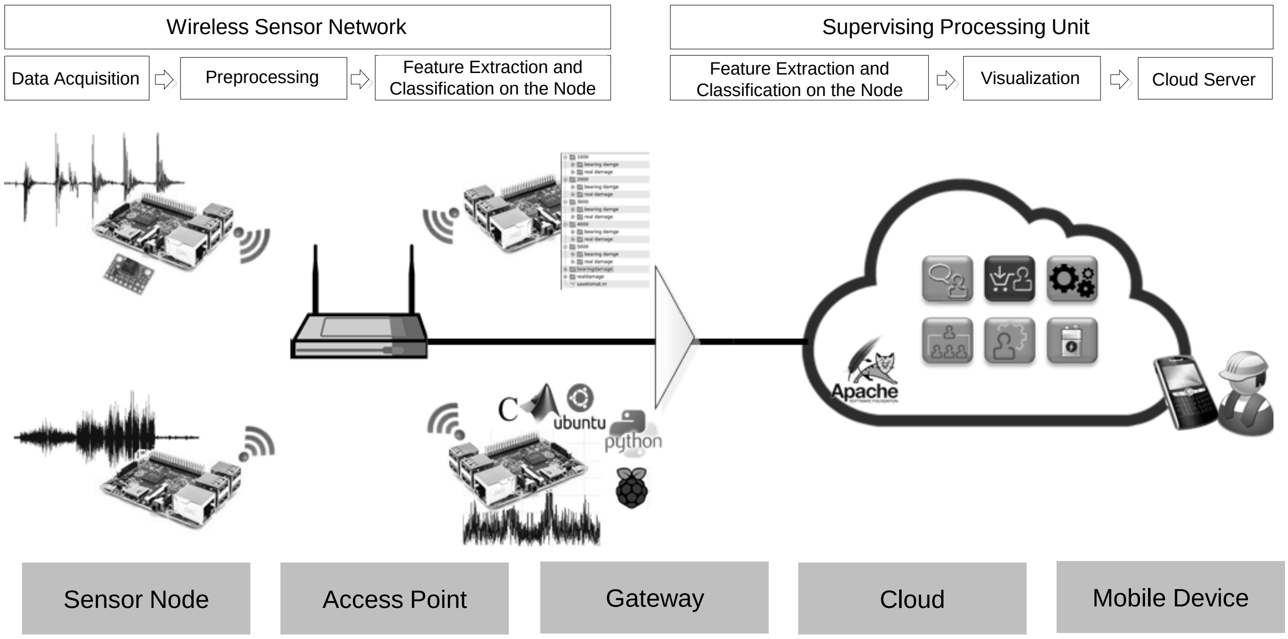


Fig. 11. Communication architecture for distributed condition monitoring on wireless sensor network (following [38])

Also in 2016, the Bosch Connected Devices and Solutions GmbH which was founded in 2013 to provide solutions for Internet-of-Things applications brought the XDK Cross Domain Development Kit to market. The battery-driven XDK was developed for prototyping in different application areas, not especially for the manufacturing industry. It can be interpreted as a kind of wireless multiple sensor node that provides MEMS based sensors for the acquisition of vibration, humidity, pressure, temperature, acoustic, brightness, magnetism and spatial orientation. For data processing and internet communication it is equipped with a microcontroller and integrated antennas. Local a micro SD card slot and a rechargeable battery [40].

## 5. CONCLUSION AND OUTLOOK

This article makes a proposal of how an intelligent production system should be characterized and provides a brief historical review of the development of intelligent production systems along the timeline of industrialization. After this, a critical discussion of the meaning of the term *Industrie 4.0* is given including an overview of international research activities. In conclusion, it is stated that, from a technological point of view, *Industrie 4.0* describes rather an evolutionary enhancement of already existing technologies than a real industrial revolution. The characteristic features of *Industrie 4.0* are ubiquitous, surrounding networking of people, machines, objects and IT-systems that will enable horizontal integration in value added networks and will break with the strict separation of the established levels of the automation pyramid. Associated therewith, manufacturing intelligence and functions will more or less change from centralization to decentralization, and this also calls for a new design of the sociotechnical system in which humans and machines collaborate in a highly distributed production environment. The article also illustrates by best practice examples from industry and research how intelligent production systems can contribute to the implementation of *Industrie 4.0*. The examples demonstrate which technological and organizational prerequisites have to be established to reach this goal.

While the principal adoption of innovative technologies in *Industrie 4.0* scenarios is on a good way, extensive research is needed to answer questions related to a beneficial use of big data and to how involved stake holders will collaborate in new business models.

Many of the principle concepts that are nowadays promoted in *Industrie 4.0* have been developed years before the idea of *Industrie 4.0* was born in 2011 – and they are still valid (cf. Table 2). Nevertheless, these technologies have become more and more powerful over the years due to enhancements. They build the technological basis for the realization of *Industrie 4.0* applications. What is needed to bring *Industrie 4.0* to success, is the courage to embrace changes. Old-established processes and concerns about innovative business models that require an overcoming of departments and corporate boundaries have to be rethought. One of the challenges that have to be mastered is to ensure transparency with simultaneous data security. Due to the fact that this is not a purely technological task, interdisciplinary cooperation and the will for change are needed.

Table 2. Relevant appearance of *Industrie 4.0* related concepts

| Concept | Year of relevant appearance | Reference |
|---|---|---|
| Industrial Product-Service Systems (IPS²) | 2007 | [41] |
| Cyber-Physical Systems (CPS) | 2006 | [42] |
| Digital Twin | 2001 | [27] |
| e-Industrial Services | 2001 | [43] |
| Big Data | 1997 | [44] |
| Cloud Computing | 1996 | [45] |
| Internet-of-Things (IoT) | 1991 | [46] |
| Computer-Integrated Manufacturing (CIM) | 1973 | [47] |
| Machine Learning | 1959 | [48] |

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