White Paper

Factory of the future

Executive summary

By tradition, manufacturing has been thought to be a process that turns raw materials into physical products, and the factory, in managing fragmented communications protocols and automation practices, is the structure where manufacturing happens. Today, drivers such as technology, sustainability, optimization and the need to meet customer demands have once again encouraged the transformation of the manufacturing industry, to become adaptive, fully connected and even cognizant of its own power quality. This transformation is characterized by the globalization of value chains in organizations, with the goal of increasing competitive advantages, creating more value add-ons and reducing costs through comprehensive sourcing. In support of this notion, one of the most significant trends in manufacturing is the makeover from industrial Ethernet and industrial wireless communications to that of improved information technology (IT) solutions involving the union of conventional automation with cyber-physical systems combining communications, information and communication technology (ICT), data and physical elements and the ability to connect devices to one another. This IT transformation, which shifts the manufacturing process from a patchwork of isolated silos to a nimble, seamless and fully integrated system of systems (SoS) matching end user requirements in the manufacturing process, can be described as factory of the future (FoF).

The advantages of having automated systems have been quickly recognized by industry. Due to the rapid evolution of IT in the second part of the 20th century, engineers are able to create increasingly complex control systems and integrate the factory floor. The automotive industry, for instance, has been transformed radically by the development of automation. Over time, the food industry as well as pharmaceutical and other manufacturing companies has also heavily relied on automation to produce more and at lower cost. This often results in higher end quality and reliability throughout the assembly chain to the advantage of the consumer.

The ultimate goal of the factory of the future is to interconnect every step of the manufacturing process. Factories are organizing an unprecedented technical integration of systems across domains, hierarchy, geographic boundaries, value chains and life cycle phases. This integration will only be a success if the technology is supported by global consensus-based standards. Internet of Things (IoT) standards in particular will facilitate industrial automation, and many initiatives (too many to list here) in the IoT standardization arena are currently underway. To keep up with the rapid pace of advancing technology, manufacturers will also need to invest in both digital technologies and highly skilled technical talent to reap the benefits offered by the fast-paced factories. Worker safety and data security are other important matters needing constantly to be addressed.

So what will the factory of the future look like and how will it be put into action? This White Paper will assess the potential worldwide needs, benefits, concepts and preconditions for the factory of the future, while identifying the business trends in related technologies as well as looking at market readiness.

Section 2 leads with the current manufacturing environment and its evolution across the centuries. The benefits of having multiple, bi-directional value chains are essential as well as supporting information optimization across organizational boundaries.

Section 3 provides a brief background on manufacturing paradigms throughout history and examines various regional concepts of new manufacturing initiatives, their underlying technologies and preconditions and their impact on different facets of the manufacturing area.

Section 4 examines the driving technologies for implementation of factory of the future concepts. Technical challenges and preconditions – many things are promised early, but take time to become existent – are also underscored as well as how to enable the necessary technologies.

Section 5 balances the adoption of new technologies with the prerequisites for market readiness.

Section 6 envisages the future landscape, with consideration being given to enabling technologies as well as some of the specific challenges involved.

Section 7 concludes with a list of recommendations for addressing the requirements related to data, people, technology and standards for factories of the future.

Acknowledgments

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Table of contents

List of abbreviations

Technical and scientific terms

AI	artificial intelligence
AIM	application infrastructure and middleware
AM	additive manufacturing
AVM	adaptive vehicle make
BOM	bill of materials
CAD	computer-aided design
CAx	computer-aided technologies
CEP	complex event processing
CNC	computer numerical control
CPPS	cyber-physical production system
CPS	cyber-physical system
DCS	distributed control system
EDI	electronic data interchange
ERP	enterprise resource planning
ESP	event stream processing
FoF	factory of the future
HMI	human-machine interface
ICT	information and communication technology
IoT	Internet of Things
IT	information technology
M2M	machine to machine
MEMS	microelectromechanical system
MES	manufacturing execution system
NFC	near field communication
PLC	programmable logic controller
QMS	quality management software
R&D	research and development
ROI	return on investment

SCADA	supervisory control and data acquisition
SIM	subscriber identity module
SoS	system of systems
WBS	work breakdown structure
XaaS	anything-as-a-service

Organizations, institutions and companies

AMO	Advanced Manufacturing Office
AMP	Advanced Manufacturing Partnership
IEC	International Electrotechnical Commission
IIC	Industrial Internet Consortium
MSB	Market Strategy Board (of the IEC)
NCOIC	Network Centric Operations Industry Consortium
SMLC	Smart Manufacturing Leadership Coalition
VDMA	Verband Deutscher Maschinen- und Anlagenbau (German Engineering Association)
ZVEI	Zentralverband Elektrotechnik- und Elektronikindustrie

Glossary

cyber-physical systems
CPS
smart systems that encompass computational components (i.e. hardware and software) and physical components seamlessly integrated and closely interacting to sense the changing state of the real world

Internet of Things
IoT
infrastructure, technologies and applications that bridge the gap between the real world and the virtual world

additive manufacturing
fully automated production of a product from a virtual model through 3D printing or use of similar technologies

horizontal integration
supply chain integration into a holistic IT landscape between different stages of production and the respective resource and information flow within a factory and across companies along the value chain

vertical integration
information integration and system interoperability across technological and business levels in production and logistics (sensor, control, production, manufacturing, execution, production planning and management level)

Section 1
Introduction

What will the production world of the future look like? How will humans and machines communicate with each other? Will our working worlds be adaptable to our needs? In the factory of the future humans will have to come to terms with an increasingly complex world of processes, machines and components. This will require new operating concepts for optimized human-machine operations. Nimble, adaptive and intelligent manufacturing processes will be the measurement of success. The combination of “virtual” and “real” in order to get a full view of the complete value chain will allow factories to produce more rapidly, more efficiently and with greater output using fewer resources. Businesses will also be able to respond more quickly to the market, serving increased demand for individual products.

At present, the majority of manufacturing plants and production facilities around the world are putting into place systems that will make them adaptive, fully connected, analytical and more efficient. These new manufacturing systems are introducing a new industrial revolution, called factory of the future (FoF). This model marks the beginning of a new phase of manufacturing characterized by complete automation and involving an increased use of technology and field devices in and outside of the manufacturing facility. It represents the convergence of the mechanical age initiated by the industrial revolution and the digital age, in which massive amounts of information can be stored and then retrieved from data banks in the blink of an eye.

Factories of the future are oriented toward ensuring the availability of all relevant information in real time through the connectivity of all elements participating in the value chain, as well as providing the ability to deduce the optimal value chain processes from this data at the demand of the individual customer. Through the interaction of humans, objects and systems a dynamic, real-time optimized and self-organizing value chain will evolve. This value chain can be multi-vendor capable and can be adjusted for different business aims, such as costs, availability and resource consumption.

The factory of the future will increase global competitiveness and will require an unprecedented integration of systems across domains, hierarchy boundaries and life cycle phases. Many factors can contribute to establishing factories of the future, but consensus-based standards are indispensable in this process.

IEC International Standards help improve plant safety, security and availability and constitute the foundation to enhance product reliability and quality. The IEC provides a platform to companies, industries and governments for meeting, discussing and developing the International Standards they require.

1.1 Scope of this White Paper

This White Paper evaluates how manufacturers, workers and customers will have to come to terms with an increasingly complex world of processes, machines and components. This will require new operating concepts for optimized human-machine cooperation. Increased efficiency, reduced time-to-market and greater flexibility will improve a factory’s ability to compete. Manufacturers not only need to enable shorter time to market but also have to increase efficiency by reducing their operating costs, minimize the utilization of natural resources and improve the safety of their products and that of their workers.

This White Paper describes how factories of the future will use a system of systems (SoS) approach in which the product to be manufactured will have available all of the data necessary for its manufacturing requirements. The resulting self-organization of networked manufacturing equipment will take into account the entire value added chain, with the manufacturing sequence being determined on a flexible basis, depending on the current situation, and with the human being remaining essential as the creative planner, supervisor and decision maker of the process.

The global smart factory market is expected to total nearly USD 67 billion by 2020, increasing at a compound annual growth rate of 6% from 2014 to 2020 [1]. Communication, automation, robotics and virtual simulation will change the product sector as we know it today. What will the production world of the future look like? How will humans and machines communicate with each other, and what role will our thoughts play?

The developed world is confronted with economic and monetary constraints that make it harder to maintain the production levels of recent years, while developing countries are recording a rapid increase in output. The result is that for those industrialized countries looking to remain competitive, one element, often neglected in the past but now an integral part of any bill of materials (BOM) calculation, is the cost of the energy used to produce the goods. In manufacturing, energy has always been viewed as a cost of doing business, an expense to be controlled and a large contributor to indirect costs. For example, many production lines continue to operate during holiday breaks and weekends, even in the absence of any workers. Since the industrial sector – which uses roughly 30% to 40% of total world energy – is highly sensitive to changing economic conditions, it follows that cost reduction measures introduced as the result of regulatory and consumer pressures are pushing companies to use energy more efficiently.

Enhanced compatibility levels can only be achieved through the existence of consistent international standards ensuring that components from different suppliers and technologies can interact seamlessly. Continued development of common standards will ensure that data can flow between automation systems without requiring an expensive conversion or interpretation of the meaning of the data if the logic is not commonly understood. IEC International Standards enable common terminologies and procedures to ensure that organizations and businesses can efficiently communicate and collaborate.

There are many initiatives underway, such as smart manufacturing, Industrie 4.0, e-Factory or Intelligent Manufacturing; however this White Paper is not about a specific programme but about a future (global) manufacturing in the long term.

This White Paper is the seventh in a series whose purpose is to ensure that the IEC can continue to address global problems in electrotechnology through its International Standards and Conformity Assessment services. The White Papers are developed by the IEC Market Strategy Board (MSB), responsible for analyzing and understanding the IEC's stakeholder environment, in order to prepare the IEC to strategically face the future.

The main objectives of this White Paper are:

- To assess potential worldwide needs and benefits for the factory of the future
- To identify the concepts and trends in related technologies and markets including value chains
- To review and assess the driving technologies and their impact
- To predict the future landscape of manufacturing, taking into account the sometimes con-

tradictory factors of market readiness versus technology maturity

- To encourage the use of international standards needed to support widespread commercialization of the supporting technologies for factories of the future

Section 2

Current manufacturing environment

It is obvious that the economy is an important aspect of society, and as the economy has evolved over time, so have societies. Over the past millennia, several major social transformations have determined the course of humanity, including the agricultural, industrial and information and service revolutions. From the extensive changes introduced by those eras, it can be seen that as shifts to a new industrial base have occurred, business models and manufacturing systems have adapted respectively, since manufacturing demands are always related to the needs of societies.

As a result, manufacturing paradigms have also evolved across the centuries. Figure 2-1 shows the development from craft manufacturing to mass production, which made a wide variety of products available for a wide range of people, followed by a shift back towards specialized and diversified production in order to reflect the individual needs of customers – but on a more efficient and high-tech level.

However, addressing product demands does not on its own make manufacturing companies competitive. It should be considered that currently

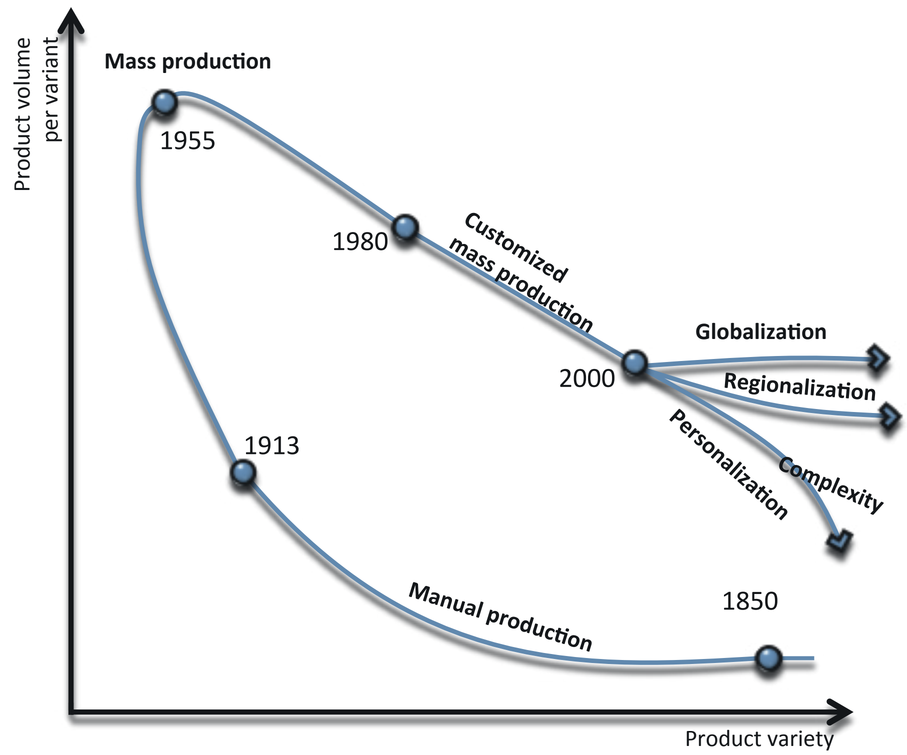

Figure 2-1 | Evolution of production [2]

manufacturing industries are undergoing rapid changes, which are driven by globalization and the exploitation of the early and late phases of production chains, as it is shown by the smile curve in Figure 2-2, since manufacturing has become the least value-adding process in the provision of products.

A close relation exists among strategies to add value and related societies – not only with regard to the kind of value added that people are willing to pay for, but also with respect to the kind of jobs that create value. For example, it is the case that manufacturing employment is decreasing globally, especially when compared to the overall level of manufacturing added value, which is increasing. This especially applies to high-wage countries, where the real output per labour hour in manufacturing could be increased by reducing labour intensity through manufacturing automation and the transformation of workers into highly-skilled experts.

In this context, socio-economic trends such as demographic changes have to be considered as well. In the manufacturing domain, this means that workplaces will have to be adapted appropriately, for example by adding intelligent assistance systems to enable workers to focus on creative and value-adding tasks and achieve a reduction of routine and stress-intensive labour, and to facilitate the transfer of knowledge among workers and manufacturing systems as a whole.

The importance of such knowledge and skills is cumulative, as products, systems and business environments become more and more complex and technology-intensive. This is leading to a trend of perceiving knowledge as capital, with the goal of using and exploiting information across traditional boundaries as successfully as possible. A company's ability to manage and use the knowledge about market, product, and production environment will increasingly exert an influence on its competitiveness and capacity for innovation.

For this reason, the exploitation of appropriate IT systems in manufacturing is essential. Depending on their degree of maturity, such systems support the management of knowledge and complexity

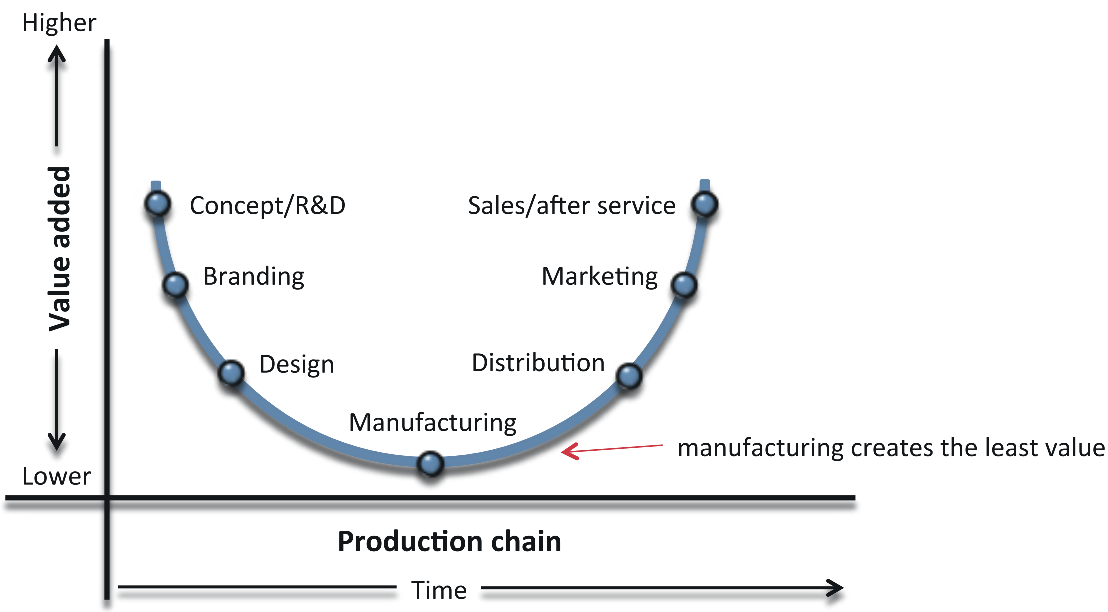

Figure 2-2 | Smile curve of value added in production industries [3]

throughout value chains, i.e. the full range of value adding activities in production across multiple organization units, via visualization, integration and connection and intelligent analysis of production systems.

With today's globalization explosion, it is clear that companies cannot survive without recognizing and integrating a multitude of value chains. Every supplier and every customer demands nuances that force companies to function as a link in any number of chains, and those chains must be viewed from a global perspective.

While dealing with multiple value chains, it is important to recognize that a company's value chain is a cornerstone of its business success. Diversity and technical advances are to be maintained by determining core competencies, ensuring effective outsourcing where appropriate and engaging in benchmarking and best practices. In other words, it is necessary to strive for supply chain excellence through visibility, collaboration, synthesis and velocity.

In modern production ecosystems, value chains need to be bi-directional, with every link supporting the flow not only of goods but of information as well. Information silos must be broken down within and between partners, if supply chain and production processes are to be optimized across organizational boundaries.

Section 3

Concepts of the factory of the future

Trends in manufacturing are moving towards seamless integration of physical and digital worlds in order to enable fast integration, feedback and control loops throughout distributed manufacturing infrastructures. As Mark Watson, senior technology analyst at the global information company IHS, explains, “stand-alone plants can also communicate with other factory sites, merging vast industrial infrastructures already in place with cloud computing and IoT. The end result is a complex but vibrant ecosystem of self-regulating machines and sites, able to customize output, optimally allocate resources and offer a seamless interface between the physical and virtual worlds of construction, assembly and production.” [4]

This overlay requires integrity and consistency of distributed data throughout the whole product and production lifecycle. To ensure this, digitization and interlinkage of distributed manufacturing systems constitute key measures for implementing the factory of the future, for example by integrating new kinds of production equipment that will be highly interconnected with one other and that will widely organize themselves, while offering a new form of decision-making support based on real-time production data arising from the production equipment and the products themselves. These new concepts of manufacturing in the factory of the future, and in related business models and technologies, will be examined within the following sub-sections.

3.1 Open value chain

As the demand for personalized products increases, product lifecycles are becoming shorter and shorter. To respond to requests arising from these changes, **value chain systems need to become more adaptable, agile and resilient and need to be optimized with regard to capital expenditure**. Accordingly, suppliers have to provide flexible machinery, which spreads investments across a wide customer base, and need to be flexibly integrated into value chains, which results in a modularization of the latter.

This keeps switching costs low and limits transaction-specific investments, even though buyer-supplier interactions can be very complex [5]. Value chain modularization also lowers the threshold for new market entrants, who previously had to invest large capital expenditures, accumulate decades of experience and build solid reputations before they could venture into a technology- and capital-intensive market [6].

Progress in IT development and its application to the logistics industry enables **close-to-real-time numerical simulation and optimization of value chain planning and execution**, while taking into consideration information such as bills of materials (BOM) and work breakdown structures (WBS), which represent the final product and value chain structure, engineering data, such as product specs, product design model and process parameters, and operational data as it is gathered from customer inquiries, design works, productions, logistics, installations, utilizations and maintenances.

As a result, manufacturing processes, production paths and resource management will no longer have to be handled by human beings, as machines and IT systems themselves will determine the best way forward: the value chain controls itself. In the process, appropriate algorithms are required, which support transparent and fair decision making in order to determine global optimums.

3.2 Flexible production

Not only do value chains as a whole have to become more flexible, singular production systems also have to adapt to fast-changing customer demands. Figure 3-1 gives an overview of the kinds of flexibility which manufacturing systems have to provide in order to adapt to changing market environments.

Individual product specifications have to be transferred to production plans, working instructions, and machine configurations which are to be distributed to the respective facilities. In the factory of the future, this process takes place automatically by means of appropriate IT interfaces and planning tools, which integrate related design and manufacturing execution systems and extract respective manufacturing settings from product configurations by means of intelligent mapping mechanisms.

However, not all adaptions can be implemented by means of material or parameter adjustments. It will also be necessary to reconfigure machines in certain cases. In doing so, it is essential to utilize standardized mechanical, electrical, and IT interfaces as well as virtual commissioning techniques in order to minimize efforts for the setup, configuration, commissioning, and ramp-up of manufacturing equipment.

To evaluate and improve production configurations, it is necessary to execute related data analytics and simulations based on actual and up-to-date information from the shop floor. For this reason, the factory of the future has to integrate various sensor systems that provide close-to-real-time data and ensure that the analysis models used represent the actual state of manufacturing systems.

3.3 Human-centered manufacturing

IT systems can introduce new relations between humans and the workplace into the factory of the future. Figure 3-2 shows a use case of the relation

Kind of flexibility	Explanation
Volume	Range of output levels that a firm can economically produce products
Product/variant	Time it takes to add or substitute new parts into the system
New design	Speed at which products can be designed and introduced into the system
Market (location/time)	Ability of the manufacturing system to adapt to changes in the market environment
Delivery	Ability of the system to respond to changes in delivery requests
Process	Number of different parts that can be produced without incurring a major setup
Automation	Extent to which flexibility is housed in the automation (computerization) of manufacturing technologies

Figure 3-1 | Kinds of manufacturing flexibility (excerpt) [7]

between humans and factories comparing past and future associations.

In the past, the relation between human and factory was relatively fixed. In a factory, the manufacturing schedule was created according to a business plan and a workforce was assembled. Workers adjusted their life to the manufacturing schedule and sacrificed their personal schedules and sometimes their health. Productivity was restricted by the degree to which workers could unite their minds with the factory.

Furthermore, in past human-factory relationships, the manufacturing knowledge was amassed in the factory. Therefore the reallocation of the acquired knowledge to other factories was difficult, and manufacturing flexibility was restricted due to this local knowledge accumulation, which led to a muffling of the productivity of the company.

Future human-factory relations will become more flexible through the use of advanced IT that supports dynamic arrangement of work-time schedules, so that personal schedules will be more respected. Also the sharing of knowledge across platforms will be enhanced and learning cycles will be shortened due to data storage, semantic technologies and the ability of the worker to merge and analyze the company's experiences with his/her own experiences for the creation of new ideas. Additionally, smart robotic technologies will be able to contribute to improvement of ergonomics in production to help address the needs of workers and support them in load intensive and routine tasks, which will provide workers with the opportunity to focus on knowledge-intensive activities. Also customer integration, which enables customer-specific, or customer-driven product design and faster joint innovation cycles, should be mentioned as a concept of focusing on humans in manufacturing.

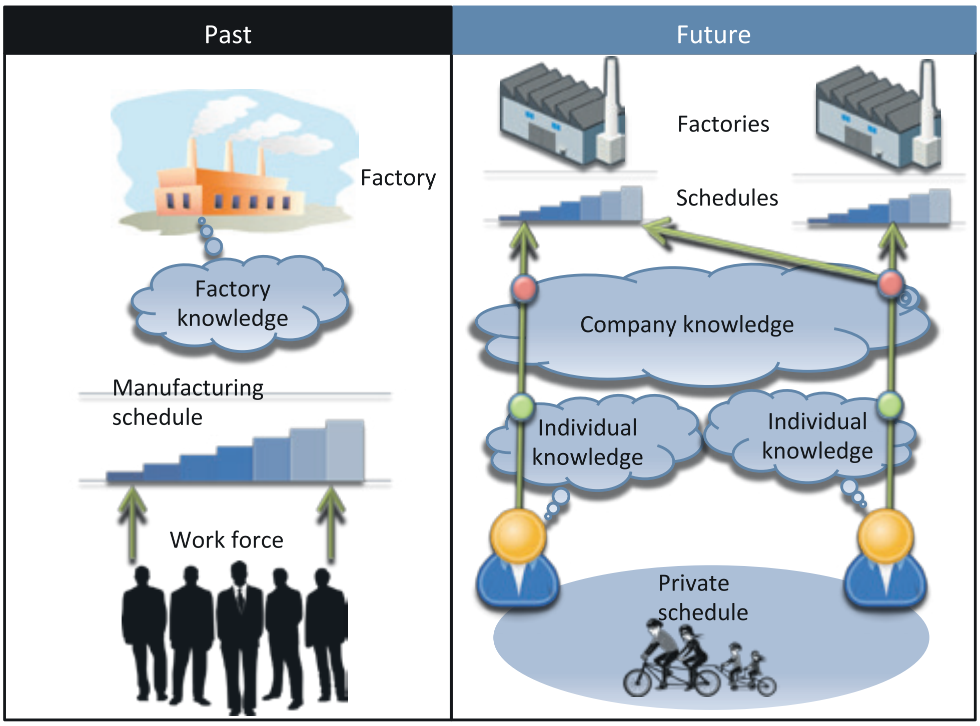

Figure 3-2 | Relation between humans and factories in the past and in the future

3.4 Business models

The increasing adoption of information and communication technologies (ICT) in the manufacturing domain not only leads to more efficient and technologically sophisticated production systems, but also enables the implementation of innovative business models. These business models are mainly driven by collaboration among manufacturing stakeholders, who have a different set of skills and expertise enabled and supported by new technologies.

An example of new technologies supporting innovative business models are micro factories. A micro factory is an international concept which encompasses the creation of miniaturized units or hybrid processes integrated with metrology, material handling and assembly to create the capability of producing small and high-precision products in a fully-automated manner, while offering the advantage of savings on both costs and resources.

Many micro factory activities are underway in this regard in Asia, especially in Japan, where micro-electromechanical systems (MEMS) micronizing both machine tool and machining technologies are expediting the application of such technologies in electronic component production, fluid machinery, construction component production and semiconductor packaging.

The main benefits of micro factories are cost efficiency, flexible production solutions, and easy management of production processes, increased productivity speed, and human resource cultivation. The following sub-sections give an overview of some of the new business models that may arise from the digitalization of production.

3.4.1 Crowdsourcing

Crowdsourcing is an ordering operation addressed to an unspecified number of people. In factory operations, as shown in Figure 3-3, a customer or factory operator announces order conditions on the site of a crowdsourcing service, such as engineering supports, temporal human resource employing, purchasing parts or facilities, etc.

In response, a member of the crowdsourcing platform proposes a plan to implement the order, potentially including quotations, and gets it if the plan satisfies the customer or factory operator.

The term crowdsourcing is a blend of “crowd” and “outsourcing” and describes the process of obtaining ideas, services or content from a large, collaborative group of participants rather than from traditionally specified employees, contractors or suppliers. That is to say, the key enabler of crowdsourcing utilization is not a top-down management, but rather cooperation between parties with respect to one another, so a management policy change is requested for this new tool application.

There are 5 main reasons leading manufacturers to leverage crowdsourcing:

1) To innovate via new perspectives and ideas coming from talent outside of the company
2) To research new concepts during the idea and development phases with people who are likely to use the company’s products
3) To design new products with better alignment to the customers’ needs
4) To fine tune the design and concept of products before they are launched onto the market, using direct feedback from potential customers
5) To flexibly integrate manufacturers for the production of new products or prototypes, for which customers do not have their own facilities

The latter motivation in particular is closely related to the **maker movement**, which is a source of (small-scale) entrepreneurship, as it is based on do-it-yourself communities and platforms pushed

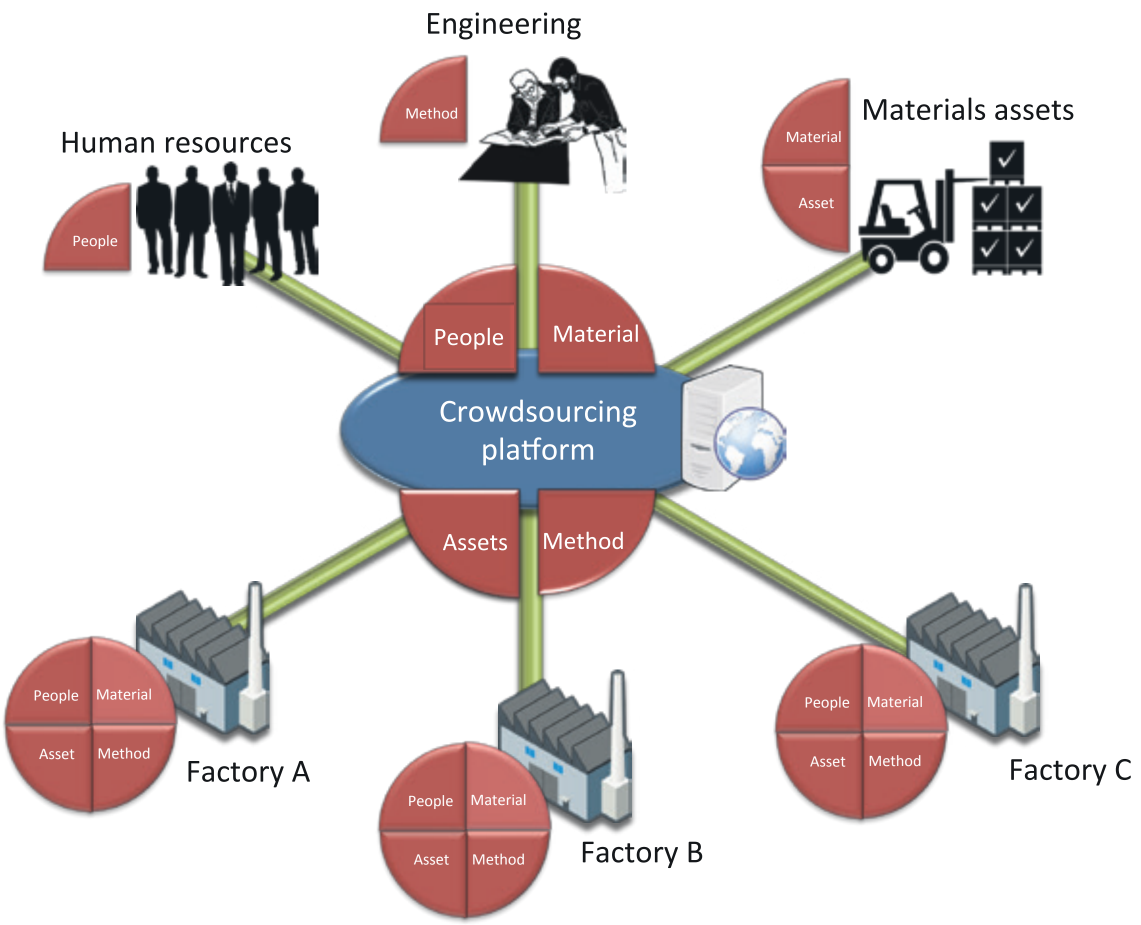

Figure 3-3 | Crowdsourcing

forward by 3D printing and other fabrication technologies.

However, several challenges must be addressed before crowdsourcing becomes a mainstream process in manufacturing. The European Union has identified 3 obstacles: the fear of change and unawareness by organizations adopting crowdsourced manufacturing solutions, intellectual property issues and a lack of design-sharing technologies [8].

Examples of companies or platforms which already exploit the crowdsourcing principles are for example Local Motors, which created the first crowdsourced production vehicle in the space of 18 months, about 5 times faster than the traditional development process [9], or DARPA's Adaptive Vehicle Make (AVM) programme which attempts to create revolutionary approaches to the design, verification, and manufacturing of complex defense systems and vehicles [10].

3.4.2 Anything-as-a-service

Similar to crowdsourcing business models, service orientation is finding its way into the manufacturing domain. Service orientation is applied to manufacturing ecosystems in order to increase their flexibility, as services are thus able to be consumed on demand, which addresses the trend towards faster reactions to changing market needs. However, anything-as-a-service (XaaS) is not restricted to product design and production, as is the case for crowdsourcing. It can involve the entire product lifecycle, including product design, manufacturing, usage, maintenance and scrap or recycling, and cannot only provide services to be executed by other persons, but also those implemented by integrating IoT components.

So it adds aspects such as **product-service integration** to the business model options, which is achieved by embedding intelligence and connectivity into both industrial and consumer products, allowing manufacturers to leverage their knowledge of the product, or to gather additional knowledge from intelligent products, in order to provide additional value-added services. It also enables them to transform their experience with the customer from a one-time transaction to an ongoing relationship. This can provide a critical new source of revenue in aftermarket services or can completely change the manufacturer's business model to one that provides performance guarantees, (semi-)automates product maintenance or even sells its product as a service.

3.4.3 Symbiotic ecosystem

In further considering crowdsourcing, XaaS and the extended degree of integration and servitization related to both, attention is focused also on other domains involving manufacturing ecosystems, such as energy and Smart Cities. As a result, global platforms which integrate diverse ecosystems in such a way as to consider the impacts they have on one another and to exploit resulting synergies enable the improvement of infrastructures beyond pure production system and production network perspectives.

"Symbiotic" is a biological term that describes multiple types of organisms living together in a mutually reciprocal relationship, in which the organisms do not harm each other, but rather live close together while providing each other with various benefits. While accepting the inevitability of constant change in external environments, structures and constituent elements, decentralized symbiotic systems provide an environment for mutually accommodating the use of limited resources between multiple autonomous systems, according to local and global system objectives as well as internal and external changes in the environment (see Figure 3-4).

In order to maintain and continue this accommodation of resources between multiple systems in a stable manner, the system providing the resources has to determine autonomously whether or not it can provide accommodations without significantly harming its ability to reach its own objectives. To realize that technologies such as distributed decision making and collaborative platforms are needed.

3.5 Local initiatives

Various local initiatives exist to address the challenges that arise from factory of the future concepts. Many of these are focusing on common topics such as efficiency improvements and personalization in production. Depending on the societal and industrial environment of the respective regions or countries, other additional key aspects such as sustainability or quality play a role. To achieve the overall objectives involved, all of the initiatives propose to exploit technologies such as IoT, additive manufacturing, and data analytics.

However, even though there is a considerable degree of congruency among the objectives and technological approaches pursued in all of the initiatives, an ongoing fragmentation exists with regard to target groups (e.g. small or large companies, focus on business models or manufacturing technology, etc.) funding policies, and standardization. Thus multiple bodies such as the Industrial Internet Consortium (IIC), Japan's e-Factory, as well as the German Industrie 4.0 platform are each defining a reference architecture model for overall factory of the future infrastructures. The

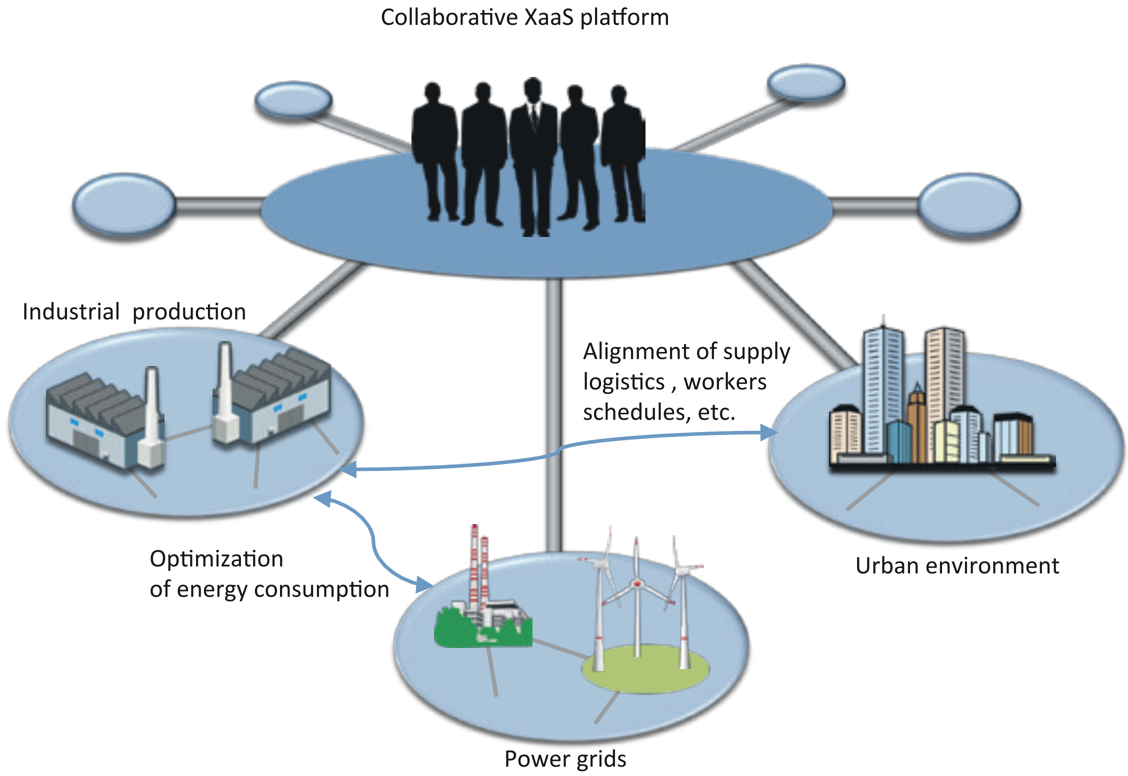

Figure 3-4 | Symbiotic ecosystem

following sub-sections give an overview of some of the major initiatives currently ongoing in the context of factory of the future.

3.5.1 Advanced manufacturing (US)

In the US, several initiatives such as the Smart Manufacturing Leadership Coalition (SMLC) [11] or the Industrial Internet Consortium (IIC) [12] are promoting the concept of advanced manufacturing, which is based on the integration of advanced new technologies such as IoT into the manufacturing area to improve produced goods and manufacturing processes.

A significant amount of study and work has been done by the Advanced Manufacturing Partnership (AMP), a steering committee reporting to the US President's Council of Advisors on Science and Technology. Their recommendations describe the basis of the initiatives sponsored by the Advanced Manufacturing Office (AMO) and the various innovation hubs being established around the US [13].

The concepts behind advanced manufacturing are also often referred to as smart manufacturing or smart production, and focus on smart products and objects in the production environment, which support product design, scheduling, dispatching, and process execution throughout factories and production networks in order to increase efficiency and enable individualization of products.

3.5.2 e-Factory (Japan)

The e-Factory concept from Japan is achieving an advanced use of the industrial internet with regard to both manufacturing control and data analytics, with the aim of effecting an optimization of productivity and energy conservation. The e-Factory approach helps to make the factory truly visible, measurable and manageable with the help of emerging technologies (see Figure 3-5).

As more data than ever before will be generated by equipment, devices, sensors and other ICT equipment, big data analytics will have the power to dramatically alter the competitive landscape of manufacturing in the future. Combining manufacturing control and big data analytics through the industrial internet will produce huge opportunities in all manufacturing areas.

Moving from current implementation to future creations, the next generation e-Factory is targeting the entire networked manufacturing supply chain, its operational efficiency and its innovation, by considering and integrating information technologies as well as enabling a continuous improvement of physical systems and pushing forward collaboration between humans. The potential significance of the next generation e-Factory approach is indeed broad: enabling technologies include sensing, smart robotics, automation of knowledge work, IoT, cloud services, 3D printing, etc. These are applied to respond to future market needs and to implement new business models.

To realize the next generation e-Factory approach, a multi-company organizational structure has been formed to enable cooperation between assemblies of companies. This partner alliance is aimed at joint product development, manufacturing, and marketing, as well as solution innovation for the entire supply chain. Meanwhile, governmental organizations have also launched investigation and studies to support the industrial companies undertaking such activities.

3.5.3 Industrie 4.0 (Germany)

Industrie 4.0, the 4th industrial revolution, is enabled by a networked economy and powered by smart devices, technologies and processes that are seamlessly connected. The vision for the 4th industrial revolution is for cyber-physical production systems which provide digital representation, intelligent services and

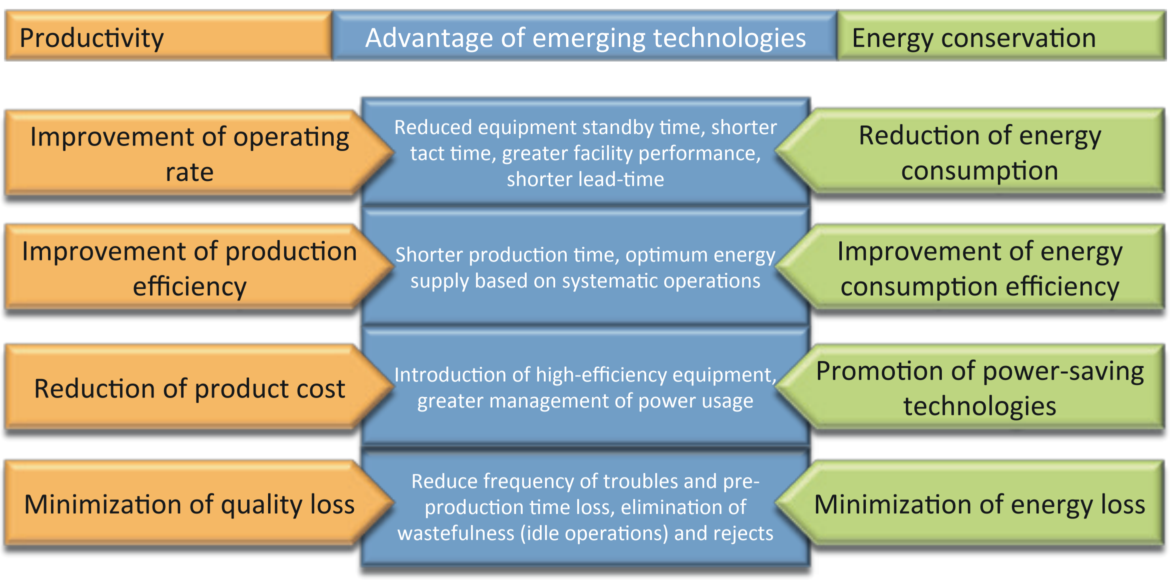

Figure 3-5 | e-Factory objectives

interoperable interfaces in order to support flexible and networked production environments. Smart embedded devices will begin to work together seamlessly, for example via the IoT, and centralized factory control systems will give way to decentralized intelligence, as machine-to-machine communication hits the shop floor.

The Industrie 4.0 vision is not limited to automation of a single production facility. It incorporates integration across core functions, from production, material sourcing, supply chain and warehousing all the way to sale of the final product. This high level of integration and visibility across business processes, connected with new technologies will enable greater operational efficiency, responsive manufacturing, and improved product design.

While smart devices can in many ways optimize manufacturing, they conversely make manufacturing far more complex. The level of complexity this creates is immense, because it not only concerns isolated smart devices, but involves the whole manufacturing environment, including various other smart devices, machines and IT systems, which are interacting across organizational boundaries.

Industrie 4.0 and its underlying technologies will not only automate and optimize the existing business processes of companies, it will also open new opportunities and transform the way companies interact with customers, suppliers, employees and governments. Examples of this are emerging business models based on usage and metering.

To push forward Industrie 4.0 applications, there exists a broad community encompassing industrial associations in Germany such as VDMA, Bitkom, and ZVEI [14], large companies and research organizations. Driven by this community, governmental initiatives such as national or regional studies and research programmes have been launched, in addition to the efforts being undertaken by industrial companies.

3.5.4 Intelligent Manufacturing (China)

China is pushing forward its Intelligent Manufacturing initiative, which will drive all manufacturing business execution by merging ICT, automation technology and manufacturing technology. The core of the idea behind Intelligent Manufacturing is to gain information from a ubiquitous measurement of sensor data in order to achieve automatic real-time processing as well as intelligent optimization decision-making. Intelligent Manufacturing realizes horizontal integration across an enterprise’s production network, vertical integration through the enterprise’s device, control and management layers, and all product lifecycle integration, from product design through production to sale.

The target of Intelligent Manufacturing is to improve product innovation ability, gain quick market response ability and enhance automatic, intelligent, flexible and highly efficient production processes and approaches across national manufacturing industries. Furthermore this initiative focuses on the transformation of manufacturing towards a modern manufacturing model involving an industry with a high-end value chain. It thereby promotes advanced manufacturing technology, the transformation and upgrading of traditional industries and the nurturing and development of strategic emerging industries.

To implement this goal, China has established the Made in China 2015 strategy, which aims at innovation, quality and efficiency in the manufacturing domain.

Section 4

Driving technologies

The implementation of factory of the future concepts requires appropriate technologies to support the seamless integration of manufacturing systems in order to enable information exchange and optimization throughout whole factories, production networks or ecosystems.

4.1 Technology challenges/needs

In applying technologies to the factory of the future, consideration should be given to the fact that these technologies should contribute to the fulfilment of various preconditions which apply to factory of the future implementations. The following sub-sections give an overview of some of these preconditions, i.e. challenges to be addressed.

4.1.1 Connectivity and interoperability

To achieve increases in efficiency, quality and individualization, as promoted by the factory of the future, bidirectional digital information flows are to be implemented. These digital information flows require tighter integration and connectivity between various components and participants in manufacturing ecosystems.

Connectivity and interoperability are defined as the ability of a system to interact with other systems without application of special effort for integration [15], for example customization of interfaces, etc. In this context, systems involve various aspects, from mechanical components and properties up to strategic objectives and business processes.

Since low-effort integration of production systems is a major enabler of factories of the future, interoperability has to be established on various levels:

- On the physical level when assembling and connecting manufacturing equipment or products
- On the IT level when exchanging information or sharing services
- On the business level, where operations and objectives have to be aligned.

Figure 4-1 visualizes these levels of interoperability

When establishing interoperability in manufacturing environments, different dimensions of integration have to be considered:

- Vertical integration, i.e. along the automation pyramid as defined by IEC 62264/IEC 61512. This includes factory-internal integration from sensors and actuators within machines up to ERP systems.
- Horizontal integration, i.e. along the value chain and throughout production networks. This includes the integration of production networks on the business level as achieved by EDI-based supply chain integration, but might include more in the future, when close-to-real-time and product- or process-specific information is exchanged to increase the level of detail and quality in distributed manufacturing optimization.
- Integration towards engineering and product/production life cycle applications (e.g. IEC 62890) in order to enable low-effort knowledge sharing and synchronization between product and service development and manufacturing environments. This is beneficial

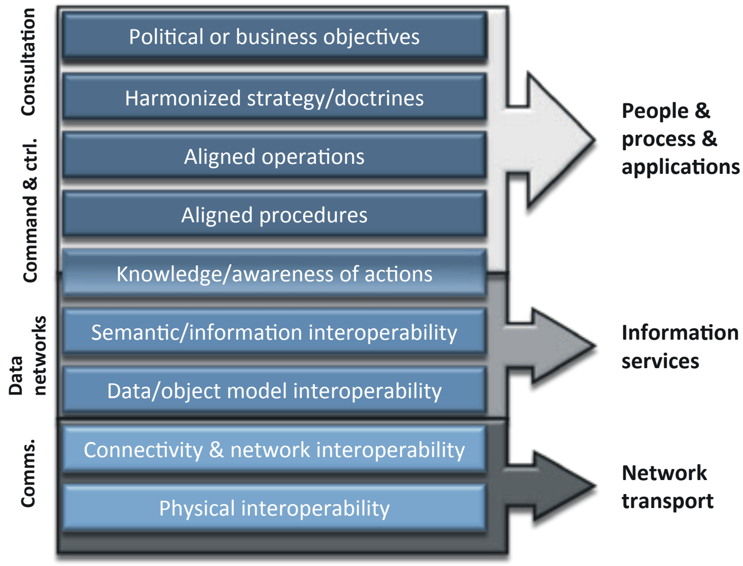

Figure 4-1 | NCOIC interoperability framework/layers of interoperability [16]

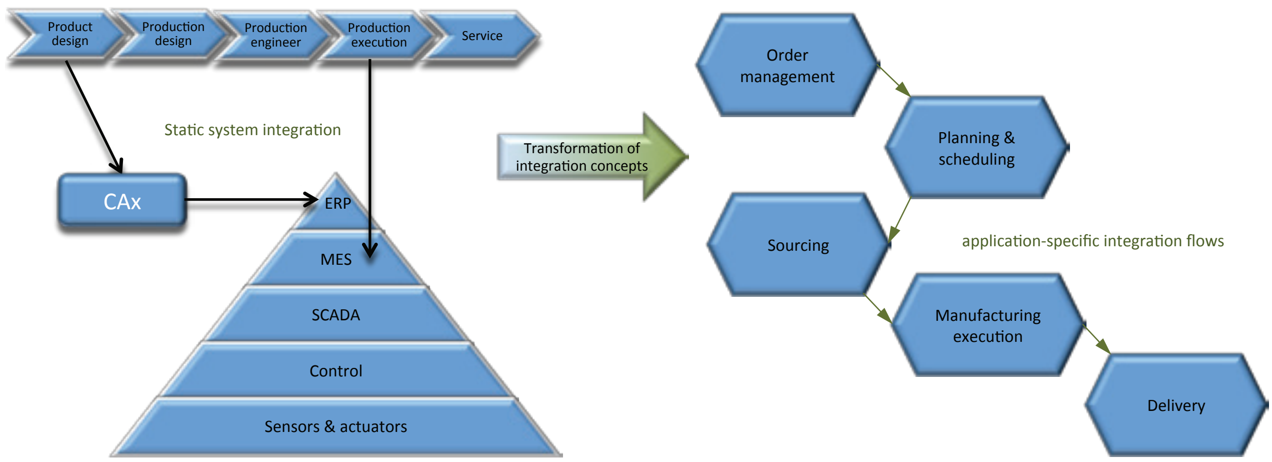

Figure 4-2 | Transformation towards factory of the future integration

for the establishment of manufacturing, when information about the products to be created should be available for planning and manufacturing configuration tasks, as well as during product development, when knowledge about the manufacturability of the respective product could be used for design optimization.

The traditional industrial value chain consists of independently implemented systems, including hardware systems (PLC, DCS, CNC, etc.) and software systems (MES, ERP, QMS, etc.), which support product design, production planning, production engineering, production execution and services, of which each has its own data formats and models, making integration of them difficult. Interoperability will blur the boundaries between these systems and activities.

Rather than sequential and hierarchical system integration, there will be a network of connected things, processes and customers that will allow companies to interact with customers and suppliers much more rapidly, accurately and effectively. As a result, implementation of specific solutions and applications in the factory of the future will not focus on system interfacing and customization, but rather on the application-specific establishment of information access and workflows. The full adoption of service-oriented architecture principles to production environments could support that.

4.1.2 Seamless factory of the future system integration

Besides connectivity and semantic interoperability, successful implementation and achievement of business value from distributed IoT-based systems require more than a framework for connecting and collecting data from devices. It requires the ability to map the business context in which such devices are applied to the management of their environment. This is to be supported by operational visibility of devices, as well as respective information model analytics mechanisms which set device information to the application-specific context, for example the specific order, product and process.

In mapping such contexts, it has to be considered that not only singular business processes such as order execution are to be enabled throughout the factory of the future system, but that various business processes such as order management, material management, etc. have to be integrated with one another. This requires the transformation of pure system connectivity, which is achieved by appropriate interfaces, towards use case-specific, integrated workflows and related information exchange, which seamlessly enable the utilization of knowledge and context information available in other systems in order to exploit as yet inaccessible optimization opportunities. To achieve this, not only systems and devices of a particular domain, such as customer and order management, have to be connected, but information sources and consumers have to be interlinked in application workflows across domains, product and production lifecycles and locations. This not only contributes to close-to-real time, application- and user-specific visibility of relevant information from any device or data source, but also might support fast and (semi-)automated decision making. So it is worth noting that not only technical issues and machine intelligence have to be addressed, but also seamless interaction with human workers, and that the utilization of their knowledge and experience has to be guaranteed and deployed as a key to ensuring seamless system integration.

4.1.3 Architecture for integrating existing systems

Most manufacturing enterprises aiming to introduce factory of the future concepts to their business already operate production systems. In such (automated) production systems, some, most, or all devices and machines are connected with control systems via various layers of automation pyramid, such as PLC, MES and ERP systems.

In order to introduce and integrate advanced factory of the future technologies, i.e. to migrate production systems stepwise towards distributed and IoT technologies, interoperability and intelligence, it is necessary to establish appropriate (IT) system architectures which support the stepwise implementation and extension of factory of the future systems, i.e. the modular roll-out of respective solutions. For the implementation of such an architecture several needs have to be considered:

- Device management and integration: In current automated systems, every sensor, device or machine has its own dialect for digital integration. A core feature of IoT solutions to be implemented in the factory of the future is connection and management of shop floor devices. Typically this requires a component running on or close to the device or machine in order to send and receive commands, events, and other data in a predefined and harmonized format to implement interoperability. This might be supported by device adapters which enable protocol and content translation to the respective integration standards. Related computing activities should be pushed as close to the device as possible to enable real-time response, data correlation across devices and machine-to-machine orchestration. Once a device is connected to the network, to other devices or to the cloud, it has to be rendered utilizable by making it visible and providing appropriate management functionalities.

- Persistence mechanisms: In order to prevent data loss during migration processes, persistence mechanisms are required that ensure the reliable transmission of information from existing systems to newly integrated ones which might replace them. Furthermore, data synchronization has to take place continuously among devices and factory of the future systems. To implement this bi-directional information exchange reliably, embedded data stores or caching mechanisms need to be deployed on the devices which have small footprints and require little administration efforts. Such data stores and caching mechanisms have to manage device configuration and connectivity, and preserve data during intermittent connection failures.

4.1.4 Modelling and simulation

Not only are flexible and seamless integration of devices, machines and software systems based on IoT technologies important, but also business context integration is a key to achieving optimization in the factory of the future.

Product and production system development and planning are becoming increasingly complex, as the number of their components, frequency of market demand changes and need for related innovation increase. To manage this complexity, product and production planning are executed incrementally with an increasing level of detail, from conceptual ideas to detailed design. In this context, conceptual design determines roughly 80% of the total costs of a product, and detailed design constitutes the critical path in terms of time and resources during product development, since domain experts create precise engineering specifications as part of the development, using domain-specific modelling and simulation tools. Unfortunately, these models cannot be combined easily – due to model, domain, and tool incompatibility – or effectively – due to performance reasons – to perform system-level analyses and simulations. Currently, only a few models and the information generated during product development are passed to the production development. The factory of the future will be supported by inter-operable models and tools that provide a harmonized view of the product from multiple viewpoints during product development – from domain-specific to system-level, and from concept design sketches to ultra-high-fidelity. Equally important will be the capability of seamlessly propagating these models and information to the production development modelling and simulation methods.

This interaction should be carried out as early as possible in order to concurrently engineer the product and its production. While some tools already integrate these models and perform simulations based on product-production information, a disconnection still exists between the tools, with only basic information being exchanged. One promising way to solve this problem may be through the creation of product-production semantics that allow production modelling and simulation tools to interact in higher-abstraction levels other than pure geometric information. Another challenge to overcome in production development is the transition from virtual models to real production. This requires that the information gathered during the virtual phase be translated into instructions, programmes, plans, and specifications, and that it be distributed to the real production systems to produce the product. This motivates development of a cyber-physical operating system or middleware to provide a functional abstraction of automation components, which other tools can interoperate with in a simpler and more efficient manner.

Conversely, feedback of knowledge about actual production systems that might contribute to the assessment and improvement of the manufacturability of the products to be designed is to be provided to respective modelling tools. Currently, both product and production are modelled based on known and well-understood assumptions, and thus fail to consider unknown and unexpected situations. In the factory of the future, the models will be continuously calibrated, and herewith optimized, according to real operating conditions.

In doing so, increasing dispersion and real-time requirements have to be considered. Improved software tools will be able to handle the real-time distributed collaboration among people and systems, within and beyond company boundaries, and also integrate additional modelling and simulation objectives such as resilience, reliability, cyber-physical security and energy efficiency, in order to measure the impact of traditional design decisions in the overall lifecycle of the product and production system.

4.1.5 Security and safety

System boundaries are extended when implementing factory of the future concepts, and the number of interfaces to remote systems increases. So do access points for potential threats from outside, which results in a need for appropriate IT security and safety measures. Moreover, system complexity increases with the increasing number of system components and the connections between them, which might cause unintended back coupling effects or the accidental overlooking of risks. To address these issues, special attention has to be paid to security and safety issues in factory of the future implementations.

4.1.5.1 Security

In the factory of the future, any physical space connected to cyber space is exposed to the potential threat of a cyber-attack, in addition to concerns regarding its physical security. To prevent such attacks, which may result in damage and liabilities, security measures are becoming increasingly important for the factory of the future. Typically, cyber security protection is defined as following the path of confidentiality, integrity and availability (C-I-A) which still applies for information system networks. However, factory of the future systems which integrate both physical space and cyber space require a protection priority that follows the path of availability, integrity and confidentiality (A-I-C).

To address system security designs, the IEC 62443, *Industrial communication networks – Network and system security* series of International Standards for industrial control systems has been developed. In order to strengthen the security of the factory of the future, the notion of control systems security needs to be broadened and additional security requirements need to be developed, in order to also handle security issues which might occur in factory of the future systems that also include information system networks.

Unexpected threats will appear during the long-term operation of factories. Therefore, the factory of the future should detect those threats responsively and react to them adaptively. Furthermore, because the various control systems of the factory of the future will rely on one other, it is important to prevent the spread of one security accident to other systems.

Overall it can be asserted that every industrial system functioning today is vulnerable, and that there is no single consistent approach to security. Currently existing security standards addressing

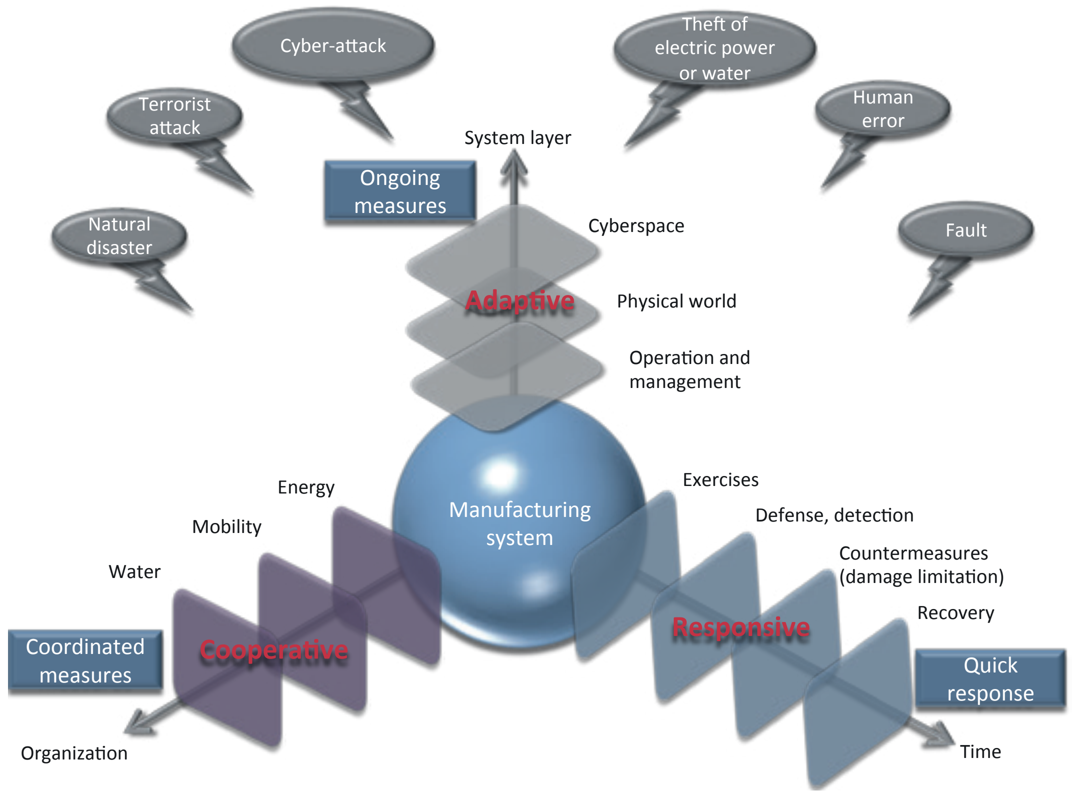

Figure 4-3 | Total concept for manufacturing system security

current requirements are not sufficient, so a continuous effort needs to be made to develop security requirements for the factory of the future.

To implement security consistently and reliably in factory of the future systems, a framework definition is required which is to be applied to the technologies adopted there. This framework has to ensure that the measures in place against possible threats are sufficient to prevent both physical and cyber-attacks to local data residencies and programmes, according to the needs of the level of the information system on which they are deployed, and that they incorporate consideration of various aspects: from human-centered physical access options to messaging systems and data residencies.

The mapping of appropriate security frameworks to reference architectures and best practice solutions can help to recommend what steps users have to undertake to increase the level of security and privacy to a specified minimum level of compliance. Thus, the owner can objectively measure and document the level of security and privacy implemented.

4.1.5.2 Safety

In addition to security, the safety of workers and equipment is also an important focus of attention when addressing accidental control system failures or intentional cyber-attacks. Up to now, actuating systems have been encapsulated with regards to control systems, i.e. external ICT mechanisms were not able to impact the behaviour of machines and other actuators in manufacturing environments.

However, due to the increasing interlinkage of industrial control systems and the automation of information exchange, this protection is no longer guaranteed. As a result, safety considerations along system boundaries in the form in which they have long been valid are not sufficient for factories of the future.

Besides issues related to system boundaries, in networks of intelligent and potentially autonomous systems there can also occur intended or unintended emergent behaviour, as such networked systems usually result in functionalities but also involve complexity and risks which go beyond that of the sum of their singular components. This also includes feedback loops that are created intentionally or by accident, and which may not only be established by interlinking systems from an IT perspective but can also emerge as the result of physical connections established, for example, by context-aware systems that recognize their environment.

However, not only systems, their boundaries and interlinkage play a role with regard to safety issues. The introduction of new manufacturing technologies used by the general public, for example AM, leads to responsibility issues. Examples of this include guarantees and accountability for failures of crowd-designed products such as cars, but also the prevention of easy manufacturing of dangerous goods such as guns.

4.2 Enabling technologies

The technological challenges described above need to be addressed by means of specific technologies in order to implement factory of the future concepts. In applying such technologies, it has to be considered that the maturity of technologies in many cases does not correspond to the expectations placed on them, since their actual industrial application usually requires a significant amount of time after promises have been made based on initial prototypes. Figure 4-4 illustrates the maturity level and future direction of technologies

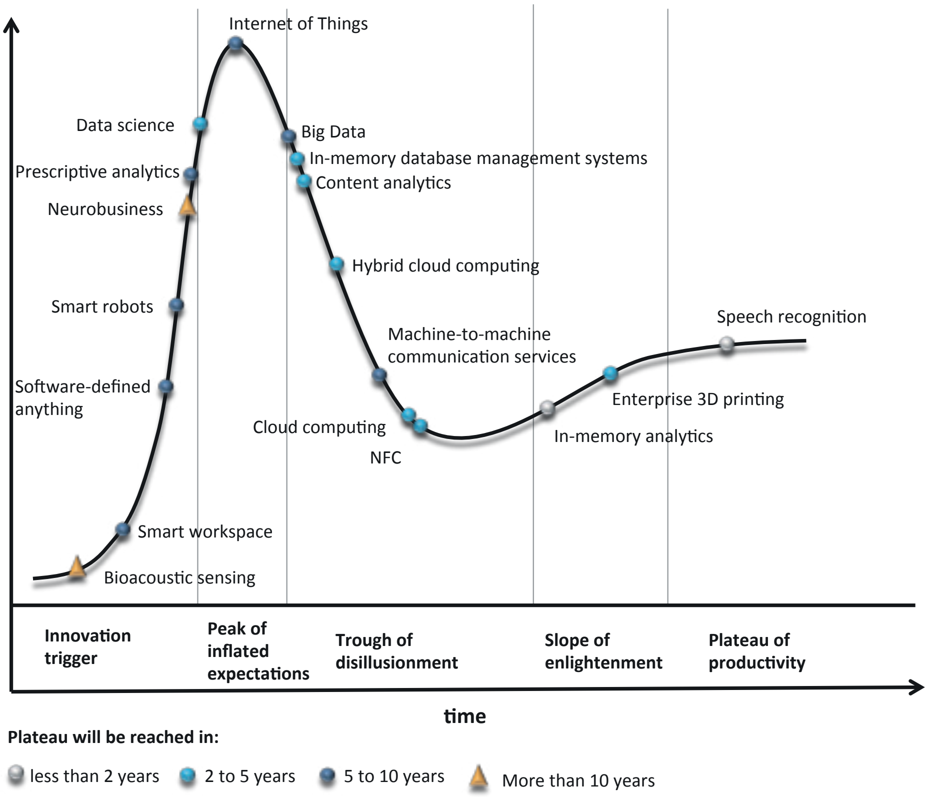

Figure 4-4 | Hype cycle for emerging technologies, 2014 [17]

which are currently regarded as emerging technologies, i.e. technologies that are observed with specific attention or that are believed will have a specific impact in the future. In the following subsections, some examples of emerging technologies thought to be relevant for the implementation of factory of the future concepts are discussed.

4.2.1 Internet of Things and machine-to-machine communication

IoT is used to link any type of objects in the physical world having a virtual representation or identity in the internet. Due to the decreased price of sensors, the small footprint of technology and ubiquitous connectivity, it is easier than ever to capture and integrate data from an ever-growing number of “things”.

The term IoT mainly derives from end consumer areas, in which more and more intelligent things are changing the daily life of people throughout the world, and use of the term is spreading to the industrial area, where machines and devices are also becoming increasingly intelligent and connected. Things that have a part or all of their functionality represented as a service based on internet technology are also referred to as cyber-physical systems (CPS) or, if particularly used in the production area, cyber-physical production systems (CPPS), both of which will be core building blocks of the factory of the future.

Machine-to-machine (M2M) communication or integration refers to the set of technologies and networks that provide connectivity and interoperability between machines in order to allow them to interact. The concept of M2M integration in industrial applications overlaps with IoT to a large extent, so that the terms are often used interchangeably, as both relate to the impact that interconnected devices will have in both the industrial and consumer worlds.

IoT and M2M technologies and solutions will affect the operational environment of manufacturers considerably, as both technologies contribute to the convergence of the classical manufacturing space with internet technologies and the increasing intelligence of devices used to improve manufacturing environments. Five main tenets explain more explicitly the connection between the technological enablers and their direct impact on manufacturing processes [18]:

1) Smart devices (i.e. products, carriers, machines, etc.) provide the raw data, analysis and closed-loop feedback that are utilized to automate and manage process control systems at every stage of manufacturing.
2) These devices are connected, embedded, and widely used.
3) As an offshoot of the proliferation of smart devices, control systems will become far more flexible, complex and widely distributed.
4) Wireless technologies will tie these distributed control modules together to enable dynamic reconfiguring of control system components.
5) Actionable intelligence will become increasingly important, because it will be impossible to anticipate and account for all of the environmental changes to which control systems will need to respond.

As shown in Figure 4-5, an IoT solution requires 3 main solution components made up of various technologies. Cyber-physical integration occurs at the edge of a network. There exists a natural hierarchy of integration at the edge, from sensors up to the cloud.

Sensors are becoming significantly more performative and less expensive, enabling manufacturers to embed smart sensors in an increasing number of sophisticated devices and machines. These machines and devices are collecting and communicating more information than ever before. In the past, automated data collection was rather the exception; now it is becoming the norm. To exploit the potentials

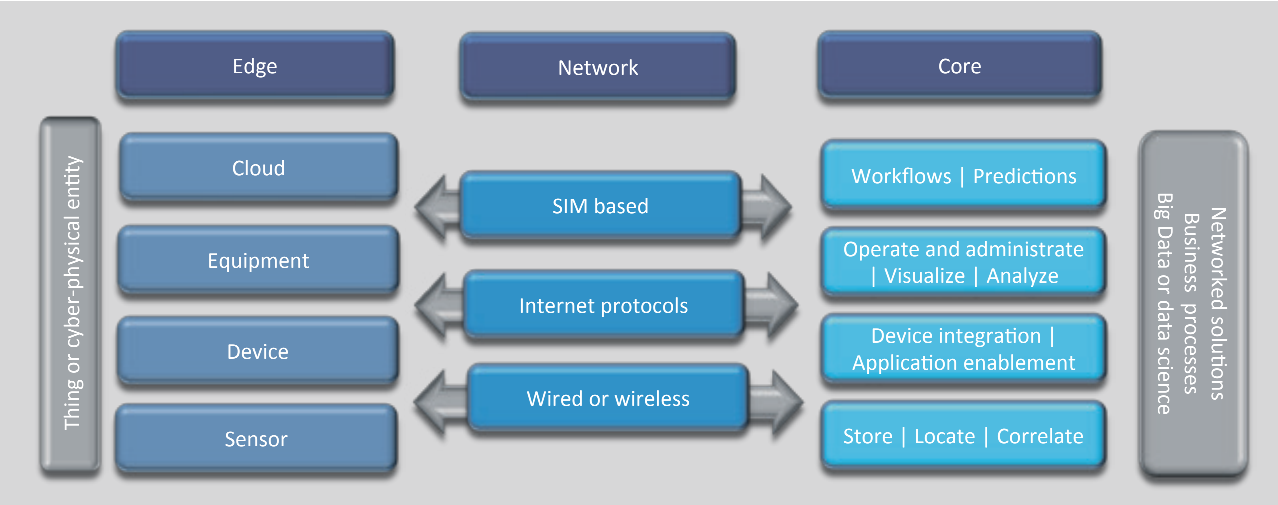

Figure 4-5 | Components of an IoT solution

which can be generated from analyzing these data, the network layer provides connectivity for all integrated devices, e.g. by means of wireless technologies, which contribute to the scalability of IoT solutions as they make it possible to increase the number of connected devices without increasing hardware efforts proportionally. Energy harvesting technologies make sensors self-dependent by converting ambient energy from various sources into usable electric power.

4.2.2 Cloud-based application infrastructure and middleware

Other key components of the IoT include computing capabilities such as cloud and fog computing. Enterprises must make choices about which information and processing can be delegated to the computing infrastructures at the edge, and which should be delegated to the internal or external processing capabilities.

Data transfer from the edge of the IoT network to processing centres must take into account the variability of device communication, ranging for example from high frequency pulses to batch uploads. Methods of data transfer from device to cloud must function regardless of whether constant and stable communication channels are available but also with intermittent disruption. Cloud technology paired with mobile devices is providing transparency and visibility of information at every location and time, even among various partners in a network.

Data collected from the ever expanding network and number of endpoints must be conveyed to processing systems that provide new business solutions and applications, whether it is through the cloud or through an internal core infrastructure. IoT solutions must have the ability to store and process large volumes of historical and diverse data and must be able to respond immediately to incoming data streams, which makes cloud and fog computing appropriate components of IoT implementations.

Accordingly, emerging cloud-based IoT solutions and vendors are providing the capability to integrate not only applications and processes but also things and sensors. Such systems can serve as the IT backbone for factories of the future and for entire supply chains, especially when the systems enable seamless intra- and inter-factory integration and facilitate dynamic scaling of device integration and computing power according to the changing needs of the manufacturer. In addition, cloud-based solutions will allow manufacturing enterprises to reduce the required core computing infrastructure and will enable them to respond flexibly to changing infrastructure needs that in turn are caused by changing requirements in the manufacturing environment.

4.2.3 Data analytics

Both IoT and cloud-based technologies increase data generation and availability in manufacturing environments. For instance, overall data generation is expected to grow by 40% per year, totalling 35 zettabytes by 2020 [19], with an estimated 25 to 50 billion connected things generating trillions of gigabytes of data [20]. For the manufacturing domain, this data will allow enterprises to monitor and control processes at a much higher level of sophistication. Previously unknown sources of incidents in shop floor processes will be identified, anticipated and prevented.

The ad-hoc availability of such a large amount of data opens new opportunities for novel types of analysis and visual representation. Batch-generated static reports are no longer state-of-the-art, as it becomes possible for users to view, chart, drill into and explore data flexibly in close to real-time, and as automated reasoning algorithms can now be applied to provide decisions that have in-process impact on manufacturing operation and optimization.

However, not only manufacturing-related data gathered by respective IoT systems is relevant for analysis. In addition to common business management systems, conditions on an inter-company level or from other ecosystems also have to be considered.

The extraction of value from the vast amount of available device data involves mining historical data for specific patterns. This requires an infrastructure that is capable of supporting the very large data sets and applying machine learning algorithms to the data. Event-driven analytics allow business rules to be established governing how to search these patterns and gather the appropriate supporting information required to analyze the situation. The point is to gather and store only the information required – the right data – as opposed to all data generated from a device, equipment or operation. These patterns can then be used to derive insights about existing and future operations. The resulting models can be incorporated into operational flows, so that as device data is received, the models generate projections, forecasts and recommendations for improving the current operational situation.

Given the amount of IoT information captured and stored, the high performance offered by such analytics systems is important. The challenge here is to know what subset of right data needs to be accessed to facilitate business process improvement and optimization. Currently, IoT data can be analyzed deeply and broadly, but not quickly at the same time. With existing technologies, optimization across all 5 dimensions in the spider diagram shown in Figure 4-6 is not possible. Trade-offs need to be made.

In-memory database computing helps to address the challenges of IoT big data, as it removes the constraints of existing business intelligence mechanisms and delivers information for making strategic as well as operational business decisions in real time, with little to no data preparation or staging effort and at high speeds allowing deep analysis of broad IoT data. Thus it provides the ability to answer questions, i.e. execute analysis on as much IoT data as it is relevant to the question, without boundaries or restrictions and without limitations as to data volume or data types. This also includes the consideration of the relevance of the data to be analyzed, since, for example, recent IoT data can be more valuable than old data.

However, the business value of in-memory computing is not only generated by the seamless integration of various kinds of data, it also enables

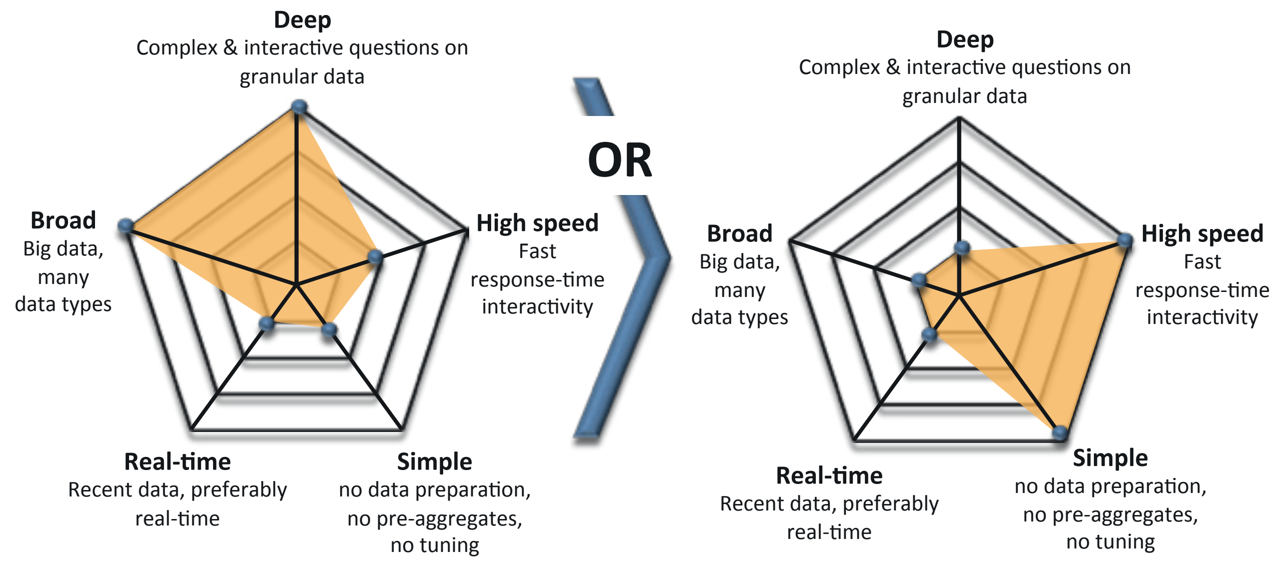

Figure 4-6 | Trade-offs on data analytics

extraction of knowledge from this data without prefabrication of information and requests. Efforts which currently are necessary in order to create, aggregate, summarize, and transform requests and data to the requested format step by step will be eliminated, as questions regarding raw IoT transactional data not prepared previously are enabled.

Additional recent data analytics capabilities include **event stream processing** (ESP) and **complex event processing** (CEP). Individual IoT data typically represents an event taking place in the manufacturing or operational environment. For example, a machine shutdown is an event; the temperature change in a process is an event; the displacement of a product from one place to another is an event. Multiple events can be related and correlated, for example, the temperature of a process increased to such an extent that a machine failed. ESP makes it possible to stream, process, filter and group all of the IoT data and events collected. ESP business rules are created to determine which events are important, which data should be filtered out and which should be kept, and which event correlations or patterns should trigger a broader business event, alert or decision.

ESP requires IoT integration to stream the data from the edge to the ESP engine for processing. CEP is a more sophisticated capability, which searches for complex patterns in an ordered sequence of events. It is ESP and CEP running on big data enabled by in-memory capability that are providing the new type of analytics available from IoT.

In order to utilize the information and knowledge which is gathered from such data analytics, **decision-making mechanisms** have to be implemented that allow IoT to drive business objectives (semi-)automatically. To do so, several options have to be compared, with the best option being selected according to current business objectives. The available options can be obtained from IoT data gathering as well as from the execution of data analytics and simulation runs. The priorities of respective business objectives might be adjusted at runtime according to changing manufacturing environment conditions.

The large volume of IoT data available from people, things and machines, along with the complexity of the processing of events and decision making, will drive the need for a unified IoT infrastructure architecture and interfaces. Such an infrastructure can serve as the basis for industrial applications which, for example, allow companies to access additional information on customer preferences and market variations, product and service creation and utilization, as well as for predictive analysis functionalities that are applied, for example, to optimize maintenance cycles.

4.2.4 Smart robotics

The emergence of IT in the manufacturing domain not only introduces new solutions, such as IoT technologies, to this field of application, but also changes existing automation and control systems, especially robotics.

For instance, **human-robot collaboration**, which is enabled by integrating real-time context awareness and safety mechanisms into robotic systems, combines the flexibility of humans with the precision, force and performance of robots. In current production systems, cell or line production is common practice, in which single workers or small teams operate various tasks in a restricted area using well-formed jigs. However, recent market demands for simultaneous application of agility, efficiency and reliability are not satisfied by such systems, which are operated solely by human ability or on fully automated lines. Robot cells, in which robots support humans in the execution of production tasks, are being developed to overcome this issue.

There exist 3 types of human-robot cooperation: synchronized cooperation, simultaneous cooperation and assisted cooperation. Figure 4-7 shows assisted cooperation as being the closest type of human-robot collaboration, in which the same component is operated by human operators and robots together without physical separation. It thus enables robots and operators to co-operate closely, for instance to handle and process products jointly in order to incorporate both the agility and reliability offered by robots and the flexibility offered by human operators.

Figure 4-7 | Human-robot collaboration

However, such collaboration presents safety issues, since failures of the involved active robot might result in fatal injuries. Moreover, currently no industry safety standards and regulations exist covering this type of human-robot collaboration, so both innovation of system integration technology and creation of new safety standards and regulations are required.

The integration of sophisticated sensors and the application of artificial intelligence (AI) enable machine vision, context awareness and intelligence. This produces collaborative robots that not only interact with humans without boundaries in a specific working area and for the execution of a well-defined task, but also anticipate required assistance needs. On one hand, this will make it possible to apply robotics to previously impossible use cases, and on the other hand it will lead to higher productivity due to the elimination of non-value adding activities for shop floor workers.

This **flexibility of collaboration** can be implemented not only for human-robot interaction but also for collaboration among robotics systems. Advanced robots can enhance sensory perception, dexterity, mobility and intelligence in real time, using technologies such as M2M communication, machine vision and sensors. This makes such robots capable of communicating or interacting much more easily with one another. The ability to connect flexibly with the surrounding environment and the recognition of the related production context make advanced robots easily adaptable to new or changing production tasks, including those which are to be executed collaboratively.

New robot programming paradigms also contribute to the low-effort implementation of new production tasks. The shift from programming robots to training robots intuitively is enabled by new robot operation engines. Trajectory points are traced manually and are then repeated by the robots. Furthermore, the skills of robots and related tools are to be managed and mapped to production process requirements (semi-) automatically. As a result, the required time for programming the robot and the necessary skill set of engineers will be significantly reduced. This will lead to an increased adoption of robots, in particular in manufacturing enterprises that previously did not apply robots due to lack of flexibility and the required programming effort.

Flexibility of robotic systems will also be increased by open robotic platforms that allow third parties to enrich robots (robot platforms) with application-specific hardware and software. Examples include special purpose grippers and associated control software. In this way, whole ecosystems (comparable to smartphones) are about to emerge. The increased flexibility afforded will lead to higher adoption of robotics in manufacturing enterprises, as robotics can be applied to a broader application area. Previously existing barriers, such as high prices, will be significantly alleviated.

4.2.5 Integrated product-production simulation

Not only innovations based on technologies on the shop floor, such as IoT technologies, data analytics and smart robotics, will have an impact on the factory of the future. The digital factory, i.e. the representation of production systems in IT systems for planning and optimization purposes, will also undergo considerable changes.

The digital factory concept refers to an integrated approach to enhancing product and production engineering processes and simulation. This vision attempts to improve product and production at all levels by using different types of simulation at various stages and levels throughout the value chain. There exist several types of simulation that create virtual models of the product and production, including discrete event simulation, 3D motion simulation, mechatronic system-level simulation, supply chain simulation, robotics simulation and ergonomics simulation, among others. The ultimate objective is to create a fully virtual product and production development, testing and optimization.

Traditionally, product and production design are separated. Product requirements have to be specified completely before the production planning and engineering phase can begin. This causes a sequential process, in which any changes produce additional costs and delays. An integrated product and production simulation will decrease time-to-market, as concurrent engineering can be performed on digital models. Visualization technologies will improve communications among geographically dispersed teams in different time zones. This integrated approach also promises a secure access to all relevant information within the company and throughout partner organizations.

Simulation tools for both products and production concentrate on various details, such as logistics regarding material routes, cycle times or buffer sizes; processes, such as assembly or machining;

or rigidity or thermal characteristics of materials. In integrated simulation applications, those specific models are shared and integrated in order to transfer knowledge and synchronize planning among specific lifecycle phases and disciplines. For instance, robotic aspects such as robot placement and path planning can be calculated by directly accessing the 3D computer-aided design (CAD) models of the products that are being manufactured. Using the results of these calculations, the PLC programmes can be automatically generated for production. Similarly, PLC programmes can be directly validated virtually using a plant-level simulation that is often referred to as virtual commissioning.

Although the trend is towards an integrated product-production simulation capability, from design to commissioning, it should be noted that feedback information loops exist that need to be put in place to take full advantage of simulation tools. For example, calibrated simulation models with data from the field can provide more accurate insights. Similarly, plant simulations can benefit from historical data from similar plants to produce optimal operating conditions.

Figure 4-8 distinguishes virtual and real worlds. In the virtual world, the product, factory and plant design first exchange information to optimize both. These designs are then turned into real world production and process automation systems that interact in order to execute production jobs. Additionally, the real world provides information to the simulated world to optimize current or future designs of products and factories, and to get

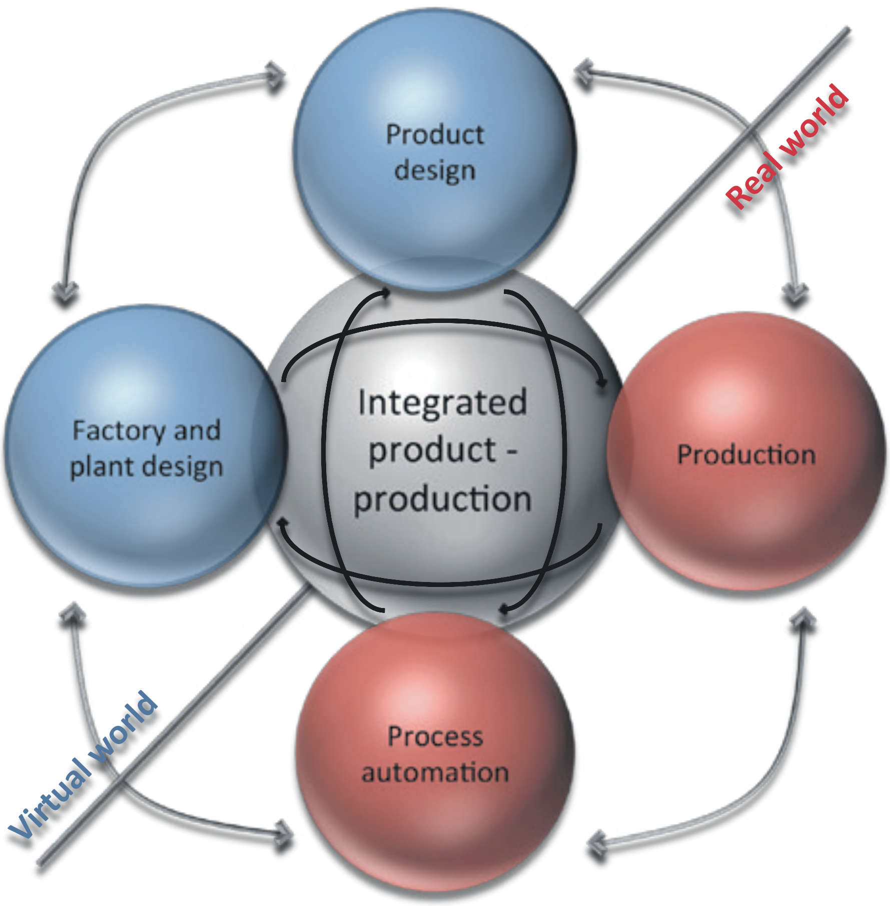

Figure 4-8 | Virtual world vs. real world

feedback about potential improvements of the actual process automation and production systems.

The emerging concept of the digital thread extends the integrated product-production simulation to the entire value chain via information feedback loops that are used to optimize continuously both the product and production, but also service, maintenance and disposal, i.e. the entire lifecycle.

4.2.6 Additive manufacturing/3D printing

A major aspect of integrating digital and physical worlds is the transfer of product specifications to executable production processes. Moreover, flexible manufacturing resources such as machining equipment or 3D printers help to keep associated configuration efforts low and thereby support the production of small lot sizes or even individual products.

The global market of additive manufacturing (AM) products and services grew 29% (compounded annual growth rate) in 2012 to over USD 2 billion in 2013 [21]. The use of AM for the production of parts for final products continues to grow. In 10 years it has gone from almost nothing to 28,3% of the total product and services revenue from AM worldwide [22]. Within AM for industry, there has been a greater increase in direct part production, as opposed to prototyping (AM's traditional area of dominance). Within direct part production, AM serves a diverse list of products and sectors, including consumer electronics, garments, jewellery, musical instruments, medical and aerospace products.

3D printing allows manufacturing to work economically with a large variety of shapes and geometries, including for small product quantities. This has the potential to transform some parts of the production industry from mass production to individual production. The "batch size one" will become more wide-spread. Furthermore, the number of required steps for producing a product will be reduced, which will lead to a more environmentally friendly production and to new shapes which improve product characteristics or enable the uses of safe materials. Another possible consequence is a shift in the role of manufacturers from designing and producing products to designing and selling the specification and plans. The actual manufacturing can then be done by others such as retailers or customers.

4.2.7 Additional factory of the future technologies

Besides these technologies, various other fields of research and development exist which might provide relevant solutions for the factory of the future, such as cognitive machines, augmented reality, wearable computing, exoskeletons, smart materials, advanced and intuitive programming techniques, or knowledge management systems.

Section 5

Market readiness

Implementation of factory of the future concepts highly depends on the readiness of involved stakeholders to adopt the appropriate technologies. Several preconditions must be fulfilled to achieve this market readiness, as explained in the following sub-sections.

5.1 Implementation of a systems perspective

The holistic implementation of factory of the future concepts requires a partnership involving the traditionally strained organizational relationships between the engineering, information technology and operations groups. Moreover, this integration of disciplines has to be implemented throughout the entire lifecycle of products and production, i.e. during planning, construction and operation.

This not only requires the interoperability of systems on a technical level, as described in Sub-section 4.1.1, but also the realization of multi-disciplinary processes, in which personnel from the engineering, information technology and business operations work closely together, understand one another or even have complementary education.

Such multidisciplinary work can be supported by appropriate IT systems, such as modelling and simulation tools, or by configuration and integration techniques for cyber-physical systems (CPS) and systems of systems (SoS). To make those solutions beneficial and to support the systems perspective during product and production planning, creation and operation, knowledge from the different disciplines has to be integrated, merged and utilized for related application purposes, and respective feedback loops have to be implemented in order to best consider potential interdependencies and enable the exploitation of additional optimization potentials or even business ideas.

5.2 Overcome "resistance to change" in traditional production environments

The interdisciplinary work not only enables more efficient information exchange and execution of work in product and production lifecycle phases. Widespread knowledge and awareness about factory of the future technologies, concepts and benefits also helps to overcome the lack of acceptance of new solutions. This lack of acceptance is caused by concerns about potential job losses due to efficiency increases generated by automation and IT systems. Knowledge and awareness are important keys to overcoming such concerns, since high levels of education reduce the risk of job losses. Furthermore, the number of jobs might not be reduced, but instead their content and style might change towards more integrative and flexible working modes. This not only concerns production jobs on the shop floor, but also PLC or robot programming and other tasks which are related to engineering.

Besides the fear of job losses, resistance to change is often caused by uncertainties on the part of stakeholders and decision makers, who are insufficiently knowledgeable about the technical background, business models and benefits involved, so that they remain restricted to well-known traditional concepts and solutions.

5.3 Financial issues

Closely related to "resistance to change" is uncertainty about the actual benefits of factory of the future implementations. In order to make sure that new factory of the future applications in manufacturing really fit the requirements of the production environment into which they should be integrated, it is necessary to assess their actual performance as soon as possible, ideally before integration decisions are made. Appropriate methods and tools, as well as best practice examples, that make it possible to secure rapid and inexpensive statements about the efficiency of certain technologies and production strategies in a company's specific production environment would help to address this need and thus reduce the threshold for implementation of new factory of the future solutions in manufacturing. Knowledge-based systems using information from previous analyses or simulation-based approval of certain decisions and virtual try-out of specific system components can contribute to this. However, such technological measures must be complemented by integration of factory of the future activities into strategic company objectives and the set-up of harmonized controlling and measurement for system performance assessment.

Besides the introduction of new IT technologies to manufacturing, business models must be evaluated with regard to their costs and benefits, in order to assess properly the potential of business innovations and reduce related risks. While transforming business through a combination of existing and emerging business models, end-to-end visibility of business value is required. This requires a standardized and shared high performance infrastructure for decision support.

However, even if the benefit of factory of the future business models and technologies is proven by respective assessments, the financial strategies of companies have to allow related investments. In this context, return on investment (ROI) predictions and the rate of capital reinvestment must be considered.

5.4 Migration strategies

In existing factories, various legacy systems are usually in place, in which relevant historical data is stored and which are connected via customized interfaces. Furthermore, the slogan "never change a running system" is widely applied in industrial production environments, in order to not jeopardize the robustness of existing production systems by integrating new features which might not necessarily be needed. To overcome these issues, while introducing new methods, concepts and technologies to factories, appropriate migration strategies are necessary.

The implementation of a systems perspective and networked and flexible organization structures for factories of the future, plus specific project management support tools designed for the needs of FoF implementation projects and appropriate rules and tools for decision making support in order to increase planning reliability, contribute to a smooth migration towards the factory of the future. Further measures to reduce the complexity and risks of migration projects include scalable (CPS) architectures that enable continuous design, configuration, monitoring and maintenance of operational capability, quality and efficiency, and the industrialization of software development, i.e. modularization to enable rapid configuration, adaption and assembly of independently developed software components.

Section 6

Predictions

Most of the key technologies for factories of the future listed in Section 4 are still under development. Their maturity and applicability in different industries, as well as the readiness to adopt them in manufacturing industries, are indicated in Figure 6-1.

From this radar plot it can be seen that in particular non-technical challenges such as migration strategies or the implementation of a system perspective are still at a premature stage. This is well in line with the observation that many of the development activities in the context of factories of the future that are ongoing at the regional, national and international levels are focusing on technological issues.

The adoption of key technologies varies among industries and application cases. For instance, additive manufacturing is appraised as being highly beneficial for personalized production and manufacturing of special parts, which, for example, have complex geometries expensive or impossible to manufacture using common manufacturing technologies. On the other side, additive manufacturing probably will never reach the degree of efficiency it already has for current mass production. Similarly, the maturity of modelling and simulation tools depends on the area of application. They are already widely used for product development and optimization, e.g. in the automotive and aerospace industry, while

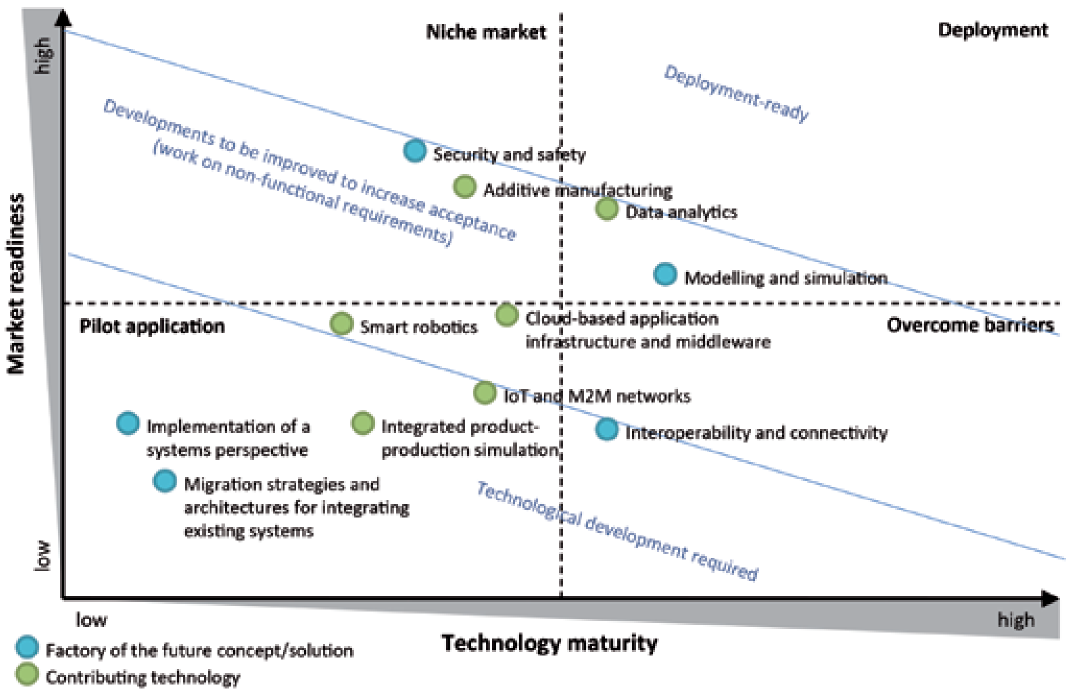

Figure 6-1 | Market readiness and technology maturity/applicability of key technologies

there is improvement potential for close-to-real-time simulation applications for optimization of manufacturing settings.

For other technologies such as IoT technologies, M2M networks, smart robotics and cloud-based AIM, singular solutions exist which are quite mature in their specific application field. However, further efforts have to be undertaken to implement wide-spread applicability of such developments by overcoming issues which are inhibiting their market readiness, such as the “resistance to change” or a lack of migration strategies.

Altogether, it can be said that the industry branch, as well as the application context, i.e. the position in the horizontal and vertical manufacturing environment layers, impact the market and deployment readiness of factory of the future applications.

Section 7
Conclusions and recommendations

The factory of the future will deliver on-demand customized products with superior quality, while still benefiting from economies of scale and offering human-centered jobs, with cyber-physical systems enabling the future of manufacturing. New manufacturing processes will address the challenges of sustainability, flexibility, innovation, and quality requirements in human-centric manufacturing. Future infrastructures will support access to information everywhere and at all times without the need for any specific installation of parameterization. Production resources will be self-managing and will connect to one another (M2M), while products will know their own production systems. This is where the digital and real worlds will merge.

A number of guiding principles and recommendations for the factory of the future emerge from the considerations covered in the previous sections. The actions involved are either of a general character or are specifically focused on data, people, technology and standards.

7.1 General

7.1.1 Interaction with other ecosystems

The IEC recommends focusing on the interaction of a factory, including all its components, such as IoT systems, with other ecosystems, such as the Smart Grid, and identifying the standards needed to allow industrial facilities and the industrial automation systems within such facilities to communicate with such ecosystems for the purpose of planning, negotiating, managing and optimizing the flow of electrical power, supply logistics, human resources, etc. and related information between them. Manufacturers should start to think of their facilities as constituting a smart node in symbiotic ecosystem networks. This will allow them to anticipate the need for demand management in a more proactive way.

7.1.2 Agile manufacturing

The adaptability of manufacturing systems to changing requirements such as market demands, business models or product specifications is a core feature of the factory of the future. To implement this, various organizational and technological measures have to be undertaken. This includes the implementation of a systems perspective, as well as solutions which enable configurability of production systems such as interoperability and connectivity, as well as their scalability. Also advanced computing capabilities, which for example enable first-time-right processing of products, are recommended in this context.

7.1.3 Maximize value chain and collaborative supply networks

The extension of network infrastructures towards production network partners will help manufacturers gain a better understanding of supply chain information that can be delivered in real time. By connecting the production line to suppliers, all stakeholders can understand the interdependencies, flow of material and process cycle times. Real time information access will help manufacturers identify potential issues as early as possible and thus prevent them, lower inventory costs and potentially reduce capital requirements.

7.1.4 Make use of independent manufacturing communities

The trend toward the "desktop factory" is not new, but it is much more pronounced today and is cheap, accessible and user-friendly. As indicated in this White Paper, the requirements posed by this trend suggest a need to make use of new business models (e.g. crowdsourcing, maker movement, product-service integrators and robotic ecosystems) to decouple design and manufacturing.

7.1.5 System safety throughout the lifecycle

The prevention and avoidance of accidental system failures or intentional cyber-attacks has to take into account the increasing interconnectedness and complexity of systems. For this reason, it is important to address system safety throughout the life cycle, from design to ramp-up and interlinkage, and to predict and evaluate the behaviour of (networked) systems in the future.

7.1.6 Sustainable security and network solutions

Security and networking solutions must be engineered to withstand harsh environmental conditions inside manufacturing facilities and to address the needs of industrial control systems, which are not present in typical "white collar" office networks.

7.2 Data

7.2.1 Service-oriented architectures

In a reconfigurable factory of the future, software will play a major role in every aspect of the value chain and on the shop floor. It is therefore important to create scalable service-oriented architectures which are able to be adapted to the specific needs of a company or factory in order to leverage all of the potential benefits that related software components bear for a factory. This includes mechanisms for the discovery, brokerage and execution of tasks.

7.2.2 Cyber security

Overall, with the expanded use of the internet for control functions in automation systems, it can be alleged that every industrial system functioning today is vulnerable, and that there is no one consistent approach to security. It is therefore critical to take the requirements for security standards seriously (i.e. corporate and personal data protection, actuating system safety, consideration of accidental feedback-loops, etc.) and to focus on safeguarding against cyber terrorism, using an adaptive, responsive and cooperative model. The IEC has a key role to play in addressing this issue.

Appropriate security frameworks are to be established that provide best practices and cost-efficient solutions according to the degrees or layers the owner of a certain set of data is willing to protect. Especially for the establishment of such frameworks among production sites or enterprises, it is also recommended to implement certification measures in order to establish trust and accelerate the setup of production networks.

7.2.3 Interpretation of data

For the large amounts of information being generated to be useful, they must be harmonized, consistent and up to date. To this end, the integration of big data and semantic technologies and their application to product lifecycle management and production systems will be necessary.

7.3 People

7.3.1 Humans and machines

The idea of human-centered manufacturing is to put the focus in manufacturing back on the employees, tailoring the workplace to their individual needs. A company can generate enormous amounts of data but ultimately it must rely on people in order to make decisions. HMI and human-centered design – the introduction of augmented reality into the automation process – allow people to visualize data in the context of the real world in order to bridge the gap between data and the physical world. Human-robot collaboration supports workers in complex or high-load tasks.

7.3.2 Training

The human operator will be supported by smart assistance systems that are interconnected with the production equipment and IT systems to help him/her make the right decisions and execute his/her tasks. This certainly will result in new skill profiles for workers, for which appropriate training will be needed. Such training is expected to occur on the job – while workers perform their daily activities, they are simultaneously learning new skills.

For the setup of factory of the future systems, cross-sectorial education is essential in order to implement, integrate and optimize the multiple components throughout all disciplines involved in product and production lifecycle phases.

7.3.3 Worker mobility

In face of the need to do more with less and the trend toward increased worker lifetimes, it is important to provide workers with an adequate workplace and continued mobility throughout their careers. As a result, the IEC emphasizes the importance of heightened development of wearables and exoskeletons that are comfortable, affordable and enable functional activities at all times.

7.4 Technology

7.4.1 Digitalization of manufacturing

Data is generated from numerous sources at all stages of the manufacturing cycle. Given that IoT and CPS produce even higher amounts of data, real-time analytics (and feedback) for this data help with the self-organization of equipment as well as with decision support. As a result, the IEC recommends that manufacturing machine designers develop their devices to be able to communicate directly with various systems within the internal and external supply chains. This will allow them to gather the necessary information about customers, suppliers, parts, tools, products, calibration and maintenance schedules. The IoT will further enable realization of the common goal of manufacturing operations, which has been to increase the number of areas in the plant where the manual data entry can be replaced with automated data collection.

Interaction between humans and CPS is another significant factor, in which human knowhow should be transformed and digitalized as one kind of data among the mass of other data. The purpose here is to equip manufacturing with the capabilities of self-awareness, self-prediction, self-maintenance, self-reconfiguration, etc. throughout the manufacturing cycle.

7.4.2 Real time simulation

Modelling and simulation will form an integral part of the entire value chain, rather than being just an R&D activity. Combining virtual simulation models and data-driven models obtained directly from the operation and making real-time simulation accessible to all activities in the factory of the future offers a great opportunity to enable new and better feedback control loops throughout the entire value chain, from design to disposal.

7.4.3 Promote cyber-physical systems

Digital information flows across company boundaries, presenting a security challenge with regard to information-sensitive activities in the value chain. Cyber security as well as physical security will be a primary concern and key performance indicator in the factory of the future. Enabling technologies such as CPS and IoT will play a fundamental role in the adoption of a more flexible connectivity in the industrial value chain. As a result, the factory of the future will be highly modular and connected.

7.5 Standards

7.5.1 Merge national concepts at the international level

A highlight for the factory of the future is that self-contained systems will communicate with and control each other cooperatively. To make this possible, international consensus-based standards taking into account existing national and regional standards for industrial automation are required. A wider market with solid standards will support the interoperability necessary for the expansion of replicable and more affordable technologies globally.

7.5.2 Systems level standardization

Keeping in line with previous IEC White Papers, *Coping with the Energy Challenge* (2010) and *Orchestrating infrastructure for sustainable Smart Cities* (2014), the MSB recommends to the IEC to ensure that standards giving preferred industrial automation solutions go beyond a simple product approach and consistently adopt a real application perspective. This will involve keeping in mind the global effects desired for the factory of the future, smart manufacturing, Industrie 4.0, e-Factory, Intelligent Manufacturing, *et al*.

7.5.3 Standardize connection protocols

Every sensor and actuator is a participant in the IoT. Each device has an IP address and is networked. In order for factories of the future to come to fruition, a portfolio of connectors and connection protocols must be available onboard any device and allow the unique dialect of each device and connector to be transformed without loss of information. The IEC should invite industry to develop standardized protocols in this area.

Annex A
References

[1] www.marketsandmarkets.com/Market-Reports/smart-factory-market-1227.html [viewed 2015-09-15]

[2] KOREN, Y., *The Global Manufacturing Revolution – Product-Process-Business Integration and Reconfigurable Systems*, Hoboken, NJ, Wiley, 2010

[3] Smile curve according to Stan Shih: chaitravi.wordpress.com/2010/02/10/the-smiling-curve-stan-shih [viewed 2015-09-15]

[4] *IEC e-tech*, May 2015: iecetech.org/issue/2015-05 [viewed 2015-09-15]

[5] www.microlinks.org/good-practice-center/value-chain-wiki/types-value-chain-governance [viewed 2015-09-15]

[6] *The Modularization of the Value Chain*, TheoryBiz.com: theorybiz.com/copycats/the-age-of-imitation/3329-the-modularization-of-the-value-chain.html [viewed 2015-09-15]

[7] D'SOUZA, D. E.; WILLIAMS, F. P., *Toward a taxonomy of manufacturing flexibility dimensions*. In: Journal of Operations Management 18(5), 2000, pp. 577-593

[8] ec.europa.eu/enterprise/policies/innovation/policy/business-innovation-observatory/case-studies/index_en.htm [viewed 2015-09-15]

[9] ABRAHAMSON, S., RYDER, P., UNTERBERG, B., *Crowdstorm: The Future of Innovation, Ideas, and Problem Solving*, John Wiley & Sons, Inc. 2013

[10] www.darpa.mil

[11] smartmanufacturingcoalition.org

[12] www.iiconsortium.org

[13] www.whitehouse.gov/sites/default/files/microsites/ostp/amp_final_report_annex_1_technology_development_july_update.pdf [viewed 2015-09-15]

[14] German Engineering Association (www.vdma.org), German association of ICT industry (www.bitkom.org), and German association of electrics and electronics industry (www.zvei.org)

[15] www.ieee.org/education_careers/education/standards/standards_glossary.html [viewed 2015-09-15]

[16] www.ncoic.org/images/technology/NIF_Pattern_Overview.pdf [viewed 2015-09-15]

[17] www.gartner.com/newsroom/id/2819918 [viewed 2015-09-15]

[18] www.forbes.com/sites/sap/2014/07/09/are-you-ready-for-the-internet-of-everything [viewed 2015-09-15]

[19] *Big Data: The Next Frontier for Innovation, Competition, and Productivity*, McKinsey Global Institute, May 2011

[20] scn.sap.com/community/internet-of-things/blog/2014/05 [viewed 2015-09-15]

[21] www.raeng.org.uk/publications/reports/additive-manufacturing [viewed 2015-09-15] p. 29

[22] www.raeng.org.uk/publications/reports/additive-manufacturing [viewed 2015-09-15] p. 5

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