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Securing the future of German manufacturing industry

Recommendations for implementing the strategic initiative INDUSTRIE 4.0

Final report of the Industrie 4.0 Working Group

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Plattform

INDUSTRIE 4.0

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Executive summary

Germany has one of the most competitive manufacturing industries in the world and is a **global leader in the manufacturing equipment sector**. This is in no small measure due to Germany's specialisation in research, development and production of innovative manufacturing technologies and the management of complex industrial processes. Germany's strong machinery and plant manufacturing industry, its globally significant level of IT competences and its know-how in embedded systems and automation engineering mean that it is extremely well placed to develop its position as a leader in the manufacturing engineering industry. Germany is thus uniquely positioned to tap into the potential of a new type of industrialisation: **Industrie 4.0**.

The first three industrial revolutions came about as a result of mechanisation, electricity and IT. Now, the introduction of the Internet of Things and Services into the manufacturing environment is ushering in a fourth industrial revolution. In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of **Cyber-Physical Systems (CPS)**. In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management. The **smart factories** that are already beginning to appear employ a completely new approach to production. Smart products are uniquely identifiable, may be located at all times and know their own history, current status and alternative routes to achieving their target state. The embedded manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. In addition, they both enable and require end-to-end engineering across the entire value chain.

Industrie 4.0 holds huge potential. Smart factories allow **individual customer requirements** to be met and mean that even one-off items can be manufactured profitably. In Industrie 4.0, **dynamic business and engineering processes** enable last-minute changes to production and deliver the ability to respond flexibly to disruptions and failures on behalf of suppliers, for example. End-to-end transparency is provided over the manufacturing process, facilitating **optimised decision-making**. Industrie 4.0 will also result in **new ways of creating value and novel business models**. In particular, it will provide start-ups and small businesses with the opportunity to develop and provide downstream services.

In addition, Industrie 4.0 will address and **solve some of the challenges facing the world today** such as resource and energy efficiency, urban production and demographic change. Industrie 4.0 enables continuous **resource productivity and efficiency** gains to be delivered across the entire value network. It allows work to be organised in a way that takes **demographic change** and social factors into account. Smart assistance systems release workers from having to perform routine tasks, enabling them to focus on creative, value-added activities. In view of the impending shortage of skilled workers, this will allow older workers to extend their working lives and remain productive for longer. Flexible work organisation will enable workers to combine their work, private lives and continuing professional development more effectively, promoting a better **work-life balance**.

Global competition in the manufacturing engineering sector is becoming fiercer and fiercer and Germany is not the only country to have recognised the trend to deploy the Internet of Things and Services in manufacturing industry. Moreover, it is not just competitors in Asia that pose a threat to German industry – the US is also taking measures to combat deindustrialisation through programmes to promote "advanced manufacturing".

In order to bring about the shift from industrial production to Industrie 4.0, Germany needs to adopt a **dual strategy**. Germany's manufacturing equipment industry should seek to maintain its global market leadership by consistently integrating information and communication technology into its traditional high-tech strategies so that it can become the leading supplier of smart manufacturing technologies. At the same time, it will be necessary to create and serve new leading markets for CPS technologies and products. In order to deliver the goals of this dual CPS strategy, the following features of Industrie 4.0 should be implemented:

- **Horizontal integration through value networks**
- **End-to-end digital integration of engineering across the entire value chain**
- **Vertical integration and networked manufacturing systems**

The journey towards Industrie 4.0 will require Germany to put a huge amount of effort into research and development. In order to implement the dual strategy, **research is required** into the horizontal and vertical integration of manufacturing systems and end-to-end integration of engineering. In addition, attention should be paid to the new social infrastructures in the workplace that will come about as a result of Industrie 4.0 systems, as well as the continued development of CPS technologies.

If Industrie 4.0 is to be successfully implemented, research and development activities will need to be accompanied by the appropriate industrial and industrial policy decisions. The Industrie 4.0 Working Group believes that action is needed in the following eight **key areas**:

- **Standardisation and reference architecture:** Industrie 4.0 will involve networking and integration of several different companies through value networks. This collaborative partnership will only be possible if a single set of common standards is developed. A reference architecture will be needed to provide a technical description of these standards and facilitate their implementation.
- **Managing complex systems:** Products and manufacturing systems are becoming more and more complex. Appropriate planning and explanatory models can provide a basis for managing this growing complexity. Engineers should therefore be equipped with the methods and tools required to develop such models.
- **A comprehensive broadband infrastructure for industry:** Reliable, comprehensive and high-quality communication networks are a key requirement for Industrie 4.0. Broadband Internet infrastructure therefore needs to be expanded on a massive scale, both within Germany and between Germany and its partner countries.
- **Safety and security:** Safety and security are both critical to the success of smart manufacturing systems. It is important to ensure that production facilities and the products themselves do not pose a danger either to people or to the environment. At the same time, both production facilities and products and in particular the data and information they contain – need to be protected against misuse and unauthorised access. This will require, for example, the deployment of integrated safety and security architectures and unique identifiers, together with the relevant enhancements to training and continuing professional development content.
- **Work organisation and design:** In smart factories, the role of employees will change significantly. Increasingly real-time oriented control will transform work content, work processes and the working environment. Implementation of a socio-technical approach to work organisation will offer workers the opportunity to enjoy greater responsibility and enhance their personal development. For this to be possible, it will be necessary to deploy participative work design and lifelong learning measures and to launch model reference projects.
- **Training and continuing professional development:** Industrie 4.0 will radically transform workers' job and competence profiles. It will therefore be necessary to implement appropriate training strategies and to organise work in a way that fosters learning, enabling lifelong learning and

workplace-based CPD. In order to achieve this, model projects and "best practice networks" should be promoted and digital learning techniques should be investigated.

- **Regulatory framework:** Whilst the new manufacturing processes and horizontal business networks found in Industrie 4.0 will need to comply with the law, existing legislation will also need to be adapted to take account of new innovations. The challenges include the protection of corporate data, liability issues, handling of personal data and trade restrictions. This will require not only legislation but also other types of action on behalf of businesses – an extensive range of suitable instruments exists, including guidelines, model contracts and company agreements or self-regulation initiatives such as audits.

- **Resource efficiency:** Quite apart from the high costs, manufacturing industry's consumption of large amounts of raw materials and energy also poses a number of threats to the environment and security of supply. Industrie 4.0 will deliver gains in resource productivity and efficiency. It will be necessary to calculate the trade-offs between the additional resources that will need to be invested in smart factories and the potential savings generated.

The journey towards Industrie 4.0 will be an evolutionary process. Current basic technologies and experience will have to be adapted to the specific requirements of manufacturing engineering and innovative solutions for new locations and new markets will have to be explored. If this is done successfully, Industrie 4.0 will allow Germany to increase its global competitiveness and preserve its domestic manufacturing industry.

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1 Introduction

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Securing the future of German manufacturing industry

Germany has one of the most competitive manufacturing industries in the world. This is due to its ability to manage complex industrial processes where different tasks are performed by different partners in different geographical locations. It has been successfully employing information and communication technology (ICT) to do this for several decades – today, approximately 90 percent of all industrial manufacturing processes are already supported by ICT. Over the past 30 years or so, the IT revolution has brought about a radical transformation of the world in which we live and work, with an impact comparable to that of mechanisation and electricity in the first and second Industrial Revolutions.[1]

The evolution of PCs into smart devices has been accompanied by a trend for more and more IT infrastructure and services to be provided through smart networks (cloud computing). In conjunction with ever greater miniaturisation and the unstoppable march of the Internet, this trend is ushering in a world where ubiquitous computing is becoming a reality.

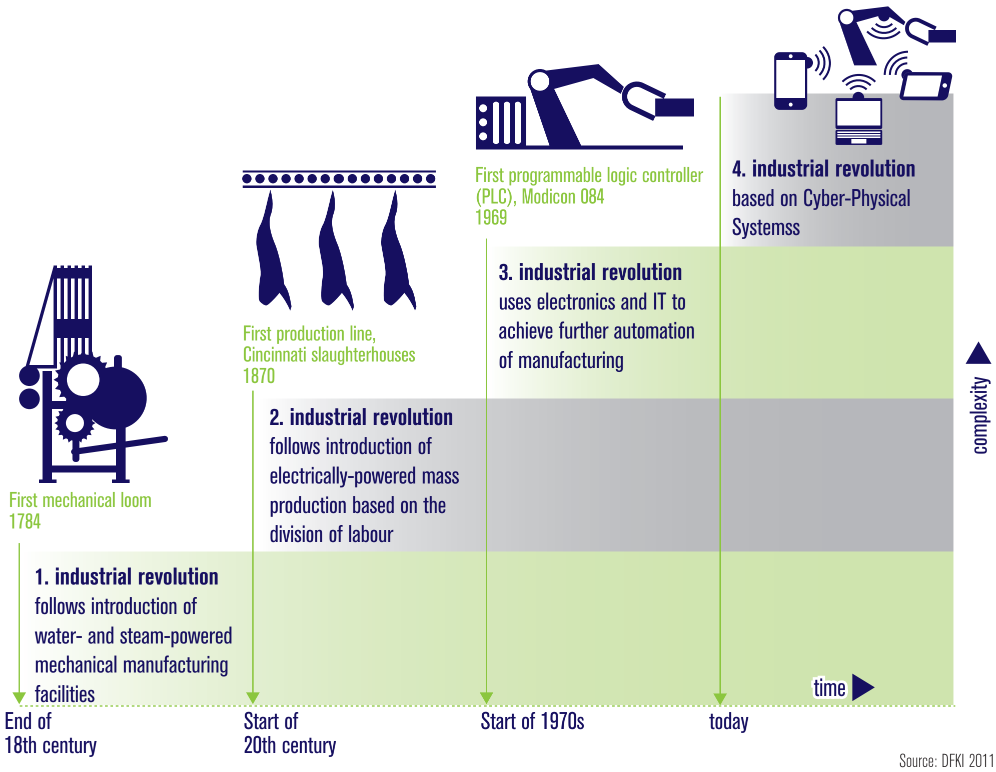
Powerful, autonomous microcomputers (embedded systems) are increasingly being wirelessly networked with each other and with the Internet. This is resulting in the convergence of the physical world and the virtual world (cyberspace) in the form of Cyber-Physical Systems (CPS). Following the introduction of the new Internet protocol IPv6[2] in 2012, there are now sufficient addresses available to enable universal direct networking of smart objects via the Internet.

This means that for the first time ever it is now possible to network resources, information, objects and people to create the **Internet of Things and Services**. The effects of this phenomenon will also be felt by industry.

In the realm of manufacturing, this technological evolution can be described as the fourth stage of industrialisation, or Industrie 4.0[3] (Fig. 1).

Industrialisation began with the introduction of mechanical manufacturing equipment at the end of the 18th century, when machines like the mechanical loom revolutionised the way goods were made. This first industrial revolution was followed by a second one that

Figure 1:
The four stages of the Industrial Revolution



began around the turn of the 20th century and involved electrically-powered mass production of goods based on the division of labour. This was in turn superseded by the third industrial revolution that started during the early 1970s and has continued right up to the present day. This third revolution employed electronics and information technology (IT) to achieve increased automation of manufacturing processes, as machines took over not only a substantial proportion of the "manual labour" but also some of the "brainwork".

Germany needs to draw on its strengths as the world's leading manufacturing equipment supplier and in the field of embedded systems by harnessing the spread of the Internet of Things and Services into the manufacturing environment so that it can lead the way towards the fourth stage of industrialisation.

Rolling out Industrie 4.0 will not only strengthen Germany's competitive position but also drive solutions to both global challenges (e.g. resource and energy efficiency) and national challenges (e.g. managing demographic change). However, it is crucial to consider technological innovations within their sociocultural context[4], since cultural and social changes are also major drivers of innovation in their own right. Demographic change, for example, has the potential to transform all the key areas of our society, such as the way that learning is organised, the nature of work and health as people live longer lives and the infrastructure of local communities. This will in turn have significant implications for Germany's productivity. By optimising the relationship between technological and social innovation processes, we will be making an important contribution to the competitiveness and productivity of the German economy.[5]

Using the Internet of Things and Services in manufacturing

The Internet of Things and Services makes it possible to create networks incorporating the entire manufacturing process that convert factories into a smart environment. Cyber-Physical Production Systems comprise smart machines, warehousing systems and production facilities that have been developed digitally and feature end-to-end ICT-based integration, from inbound logistics to production, marketing, outbound logistics and service. This not only allows production to be configured more flexibly but also taps into the opportunities offered by much more differentiated management and control processes.

In addition to optimising existing IT-based processes, Industrie 4.0 will therefore also unlock the potential of even more differentiated tracking of both detailed processes and overall effects at a global scale[6] which it was previously impossible to record. It will also involve closer cooperation between business partners (e.g. suppliers and customers) and between employees, providing new opportunities for mutual benefit.[7]

As the world's leading manufacturing equipment supplier, Germany is uniquely well placed to tap into the potential of this new form of industrialisation.[8] Germany's global market leaders include numerous "hidden champions" who provide specialised solutions – 22 of Germany's top 100 small and medium-sized enterprises (SMEs) are machinery and plant manufacturers, with three of them featuring in the top ten.[9] Indeed, many leading figures in the machinery and plant manufacturing industry consider their main competitors to be domestic ones.[10] Machinery and plant also rank as one of Germany's main exports alongside cars and chemicals.[11] Moreover, German machinery and plant manufacturers expect to maintain their leadership position in

The Internet of Things and Services is coming to the manufacturing environment:

In essence, Industrie 4.0 will involve the technical integration of CPS into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organisation.

» Industrie 4.0 offers Germany the chance to further strengthen its position as a manufacturing location, manufacturing equipment supplier and IT business solutions supplier. It is encouraging to see that all the stakeholders in Germany are now working closely together through the Industrie 4.0 Platform in order to move ahead with implementation. «

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the future. 60% of them believe that their technological competitive advantage will increase over the next five years, while just under 40% hope to maintain their current position.[12] Nonetheless, global competition in the manufacturing engineering sector is becoming fiercer and fiercer. And it is not just competitors in Asia that pose a threat to German industry – the US is also taking measures to combat deindustrialisation through programmes to promote "advanced manufacturing". Furthermore, manufacturing is becoming more dynamic and complex all the time. For example, advances in laser sintering technology mean that it is now possible to "print" complex 3D structures to a high quality standard within a matter of hours. This is resulting in the emergence of completely new business models and services where the end customer is much more closely involved – customers can create their own designs and e-mail them to a "copyshop", or they can have objects scanned and "copied".

On the initiative of the Industry-Science Research Alliance, the partners in the Industrie 4.0 Platform have therefore set themselves the goal of implementing the German government's strategic initiative to secure the competitiveness of German industry.[13]

The Industrie 4.0 initiative has huge potential:

- **Meeting individual customer requirements**
  Industrie 4.0 allows individual, customer-specific criteria to be included in the design, configuration, ordering, planning, manufacture and operation phases and enables last-minute changes to be incorporated. In Industrie 4.0 it is possible to manufacture one-off items and have very low production volumes (batch size of 1) whilst still making a profit.

- **Flexibility**
  CPS-based ad *hoc* networking enables dynamic configuration of different aspects of business processes, such as quality, time, risk, robustness, price and eco-friendliness. This facilitates continuous "trimming" of materials and supply chains. It also means that engineering processes can be made more agile, manufacturing processes can be changed, temporary shortages (e.g. due to supply issues) can be compensated for and huge increases in output can be achieved in a short space of time.
- **Optimised decision-taking**
  In order to succeed in a global market, it is becoming critical to be able to take the right decisions, often at very short notice. Industrie 4.0 provides end-to-end transparency in real time, allowing early verification of design decisions in the sphere of engineering and both more flexible responses to disruption and global optimisation across all of a company's sites in the sphere of production.
- **Resource productivity and efficiency**
  The overarching strategic goals for industrial manufacturing processes still apply to Industrie 4.0: delivering the highest possible output of products from a given volume of resources (resource productivity) and using the lowest possible amount of resources to deliver a particular output (resource efficiency). CPS allows manufacturing processes to be optimised on a case-by-case basis across the entire value network. Moreover, rather than having to stop production, systems can be continuously optimised during production in terms of their resource and energy consumption or reducing their emissions.[14]
- **Creating value opportunities through new services**
  Industrie 4.0 opens up new ways of creating value and new forms of employment, for example through downstream services. Smart algorithms can be applied to the large quantities of diverse data (big data) recorded by smart devices in order to provide innovative services. There are particularly significant opportunities for SMEs and startups to develop B2B (business-to-business) services for Industrie 4.0.
- **Responding to demographic change in the workplace**
  In conjunction with work organisation and competency development initiatives, interactive collaboration between human beings and technological systems will provide businesses with new ways of turning demographic change to their advantage. In the face of the shortage of skilled labour and the growing diversity of the workforce (in terms of age, gender and cultural background), Industrie 4.0 will enable diverse and flexible career paths that will allow people to keep working and remain productive for longer.
- **Work-Life-Balance**
  The more flexible work organisation models of companies that use CPS mean that they are well placed to meet the growing need of employees to strike a better balance between their work and their private lives and also between personal development and continuing professional development. Smart assistance systems, for example, will provide new opportunities to organise work in a way that delivers a new standard of flexibility to meet companies' requirements and the personal needs of employees. As the size of the workforce declines, this will give CPS companies a clear advantage when it comes to recruiting the best employees.
- **A high-wage economy that is still competitive**
  Industrie 4.0's dual strategy will allow Germany to develop its position as a leading supplier and also become the leading market for Industrie 4.0 solutions.

However, Industrie 4.0 will not pose an exclusively technological or IT-related challenge to the relevant industries. The changing technology will also have far-reaching organisational implications, providing an opportunity to develop new business and corporate models and facilitating greater employee engagement. Germany successfully implemented the third Industrial Revolution ("Industrie 3.0") during the early 1980s by delivering more flexible automated manufacturing through the integration of Programmable Logic Controllers (PLCs) into manufacturing technology whilst at the same time managing the impact on the workforce through an approach based on social partnership. Its strong industrial base, successful software industry and know-how in the field of semantic technologies[15] mean that Germany is extremely well-placed to implement Industrie 4.0. It should be possible to overcome the current obstacles, such as technology acceptance issues or the limited pool of skilled workers on the labour market. However, it will only be possible to secure the future of German industry if all the relevant stakeholders work together to unlock the potential offered by the Internet of Things and Services for manufacturing industry.

Since 2006, the German government has been promoting the Internet of Things and Services[16] under its High-Tech Strategy. Several technology programmes have also been successfully launched. The Industry-Science Research Alliance is now progressing this initiative at a cross-sectoral level through the Industrie 4.0 project. The establishment of the Industrie 4.0 Platform with a Secretariat provided jointly by the professional associations BITKOM, VDMA and ZVEI was the logical next step in its implementation. The next task will be to produce R&D roadmaps for the key priority themes.

Securing the future of German manufacturing industry – this is the goal that the partners in the Industrie 4.0 Platform have set themselves. The Platform invites all the relevant stakeholders to continue exploring the opportunities provided by Industrie 4.0 so that together we can help to ensure successful implementation of its revolutionary vision.

1 "Over the past thirty years, the ongoing computer revolution has transformed the world in which we live, probably more radically than anything in the previous 200 years. It has also had a radical impact on the world of work that can only be compared in scale to the first Industrial Revolution." Quotation from Kornwachs, Klaus: Ergänzung und Verdrängung der Arbeit durch Technik – Eine Herausforderung für die Technikwissenschaften (Enhancement and Replacement of Jobs by Technology – a challenge for engineering science), in: ibid. (Ed.): Bedingungen und Triebkräfte technologischer Innovationen (Enablers and Drivers of Technological Innovation) (acatech DISCUSSES), Fraunhofer IRB Verlag, Stuttgart 2007, p. 177

2 Launched in the summer of 2012, Internet Protocol Version 6 (IPv6) replaces the previous version 4 of the protocol. IPv6 uses 128-bit IP addresses instead of the 32-bit addresses that were previously in use, increasing the number of addresses available from 4.3 billion to 340 sextillion.

3 The phenomenon that we refer to as Industrie 4.0 is given different names around the globe. Other terms used include the "Industrial Internet" and the "3rd Industrial Revolution", see also Chapter 6.

4 For more on innovation and future technology scenarios, see acatech (Ed.): Technikzukünfte. Vorausdenken – Erstellen – Bewerten (Future Technology Scenarios. Planning, Production and Evaluation) (acatech IMPULSE), Heidelberg et al.: Springer Verlag 2012, p.16, which contains the following observation: "When thinking about the future, it is crucial to avoid considering technological innovations outside of their sociocultural context. For example, the future role of different energy carriers will be largely determined by how well they are accepted by society, the state of the economy and the global political situation. Terms like 'innovation systems' and 'culture of innovation' bear witness to the recent trend to place greater emphasis on this broader sociocultural context."

5 This report focuses on discussing the potential of Industrie 4.0 with regard to technological innovation.

6 Globalised manufacturing is already a reality today, as witnessed in the automotive industry, for example. "German" cars are in fact now international products made with components from Asia, Europe and the US and are even assembled in their respective target markets. However, the use of information technology in this context has hitherto largely failed to reflect the existence of these logistics and manufacturing networks. Currently, IT systems still tend not to cross company or factory boundaries.

7 A look at the past also demonstrates IT's huge potential for changing the way we do things: "From a technical perspective, an end-to-end information flow will be key to future factory designs, with electronic data processing enabling all parts of the factory to be connected to each other through a global information system. The highest level of computerised factory organisation is characterised by a strategy for integrating the individual subsystems.", in: Spur, Günther: Evolution der industriellen Produktion, in Spur, Günther (Ed.): Optionen zukünftiger Produktionssysteme, Berlin, Akademie Verlag 1997, p. 23.

8 With annual sales totalling 200.5 billion euros and a workforce of around 931,000 (average figure for 2011), the machinery and plant manufacturing industry is an extremely important part of the German economy.

9 Wirtschaftswoche Ranking, WiWo, 4/2013, pp. 40-50.

10 VDMA: Tendenzbefragung. Internationale Wettbewerbsposition des deutschen Maschinen- und Anlagebaus (Survey of Current Trends. Global Competitive Position of German Machinery and Plant Manufacturers), October 2012.

11 Federal Statistical Office, figures for 2011. Available online at: http://de.statista.com/statistik/daten/studie/151019/umfrage/exportgueter-aus-deutschland/

12 VDMA: Tendenzbefragung. Internationale Wettbewerbsposition des deutschen Maschinen- und Anlagebaus (Survey of Current Trends. Global Competitive Position of German Machinery and Plant Manufacturers), October 2012.

13 See the German government's High-Tech Strategy (HTS) Action Plan, Strategic Initiative Industrie 4.0, p. 52ff. Available online at: http://www.bmbf.de/pub/HTS-Aktionsplan.pdf

14 See Vogel-Heuser, Birgit et al.: Forschungsfragen in "Produktautomatisierung der Zukunft" (Research Issues in "Future Product Automation"), (acatech MATERIALS), Munich 2012, p. 28.

15 Under the auspices of the "Internet of Services" flagship project, the German government funded the THESEUS research programme between 2007 and 2012 in order to promote the development and trialling of new, Internet-based knowledge infrastructures geared towards making better use and maximising the value of the knowledge available through the Internet. The research programme focused on semantic technologies that, instead of detecting content (words, images, sounds) using conventional approaches (e.g. letter combinations), are capable of recognising and classifying the semantic content of information. More information is available online at: http://www.bmwi.de/DE/Themen/Digitale-Welt/Internet-der-Zukunft/internet-der-dienste,did=360458.html

16 For more details, see: Promotorengruppe Kommunikation der Forschungsunion Wirtschaft – Wissenschaft (Ed.): Im Fokus: Das Zukunftsprojekt Industrie 4.0 – Handlungsempfehlungen zur Umsetzung (Communication Promoters Group Report), Berlin, 2012.

2 The vision: Industrie 4.0 as part of a smart, networked world

2 The vision: Industrie 4.0 as part of a smart, networked world

In a "smart, networked world", the Internet of Things and Services will make its presence felt in all of the key areas.[1] This transformation is leading to the emergence of smart grids in the field of energy supply, sustainable mobility strategies (smart mobility, smart logistics) and smart health in the realm of healthcare. In the manufacturing environment, vertical networking, end-to-end engineering and horizontal integration across the entire value network of increasingly smart products and systems is set to usher in the fourth stage of industrialisation – "Industrie 4.0".

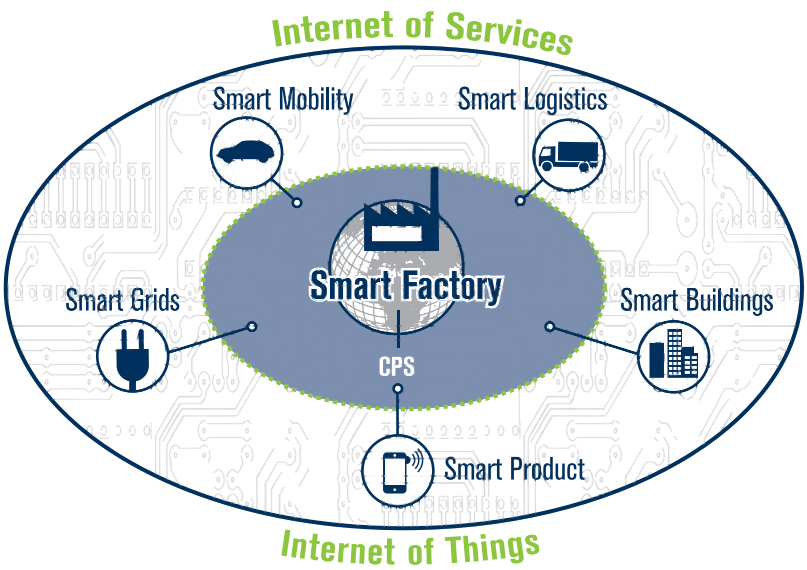
Industrie 4.0 is focused on creating smart products, procedures and processes. Smart factories constitute a key feature of Industrie 4.0. Smart factories are capable of managing complexity, are less prone to disruption and are able to manufacture goods more efficiently. In the smart factory, human beings, machines and resources communicate with each other as naturally as in a social network. Smart products know the details of how they were manufactured and how they are intended to be used. They actively support the manufacturing process, answering questions such as "when was I made?", "which parameters should be used to process me?", "where should I be delivered to?", etc. Its interfaces with smart mobility, smart logistics and smart grids will make the smart factory a key component of tomorrow's smart infrastructures. This will result in the transformation of conventional value chains and the emergence of new business models.[2]

Industrie 4.0 should therefore not be approached in isolation but should be seen as one of a number of key areas where action is needed. Consequently, Industrie 4.0 should be implemented in an interdisciplinary manner and in close cooperation with the other key areas (see Fig. 2).

2.1 Shaping the vision of Industrie 4.0

Achieving the paradigm shift required to deliver Industrie 4.0 is a long-term project and will involve a gradual process. Throughout this process, it will be key to ensure that the value of existing manufacturing systems is preserved. At the same time, it will be necessary to come up with migration strategies that deliver benefits from an early stage (see also Chapters 3 and 5.4). Nevertheless, innovations constituting a quantum leap may arise in some individual sectors.

Figure 2:
Industry 4.0 and smart factories as part of the Internet of Things and Services



In the fields of production and automation engineering and IT, **horizontal integration** refers to the integration of the various IT systems used in the different stages of the manufacturing and business planning processes that involve an exchange of materials, energy and information both within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks). The goal of this integration is to deliver an end-to-end solution.

In the fields of production and automation engineering and IT, **vertical integration** refers to the integration of the various IT systems at the different hierarchical levels (e.g. the actuator and sensor, control, production management, manufacturing and execution and corporate planning levels) in order to deliver an end-to-end solution.

If German industry is to survive and prosper, it will need to play an active role in shaping this fourth industrial revolution. It will be necessary to draw on the traditional strengths of German industry and the German research community:

- Market leadership in machinery and plant manufacturing
- A globally significant cluster of IT competencies
- A leading innovator in embedded systems and automation engineering
- A *highly-skilled* and highly-motivated workforce
- Proximity to and in some cases close cooperation between suppliers and users
- Outstanding research and training facilities

In implementing Industrie 4.0, the aim is to create an optimal overall package by leveraging existing technological and economic potential through a systematic innovation process drawing on the skills, performance and know-how of Germany's workforce. Industrie 4.0 will focus on the following overarching aspects:

- Horizontal integration through value networks
- End-to-end digital integration of engineering across the entire value chain
- Vertical integration and networked manufacturing systems

These aspects are considered in more detail in Chapter 3 in the context of the dual strategy.

2.2 What will the future look like under Industrie 4.0?

Industrie 4.0 will deliver greater flexibility and robustness together with the highest quality standards in engineering, planning, manufacturing, operational and logistics processes. It will lead to the emergence of dynamic, real-time optimised, self-organising value chains that can be optimised based on a variety of criteria such as cost, availability and resource consumption. This will require an appropriate regulatory framework as well as standardised interfaces and harmonised business processes.

The following aspects characterise the **vision for Industrie 4.0**:

- It will be characterised by a **new level of socio-technical interaction** between all the actors and resources involved in manufacturing. This will revolve around networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems. As a key component of this vision, **smart factories** will be embedded into inter-company value networks and will be characterised by end-to-end engineering that encompasses both the manufacturing process and the manufactured

» The Internet of Things and Services harbours huge potential for innovation in manufacturing. If we also succeed in integrating Web-based services into Industrie 4.0 we will increase the scope of this potential immeasurably. «

Dr. Johannes Helbig
Deutsche Post AG
Member of the Communication Promoters Group of the Industry-Science Research Alliance

product, achieving seamless convergence of the digital and physical worlds. Smart factories will make the increasing complexity of manufacturing processes manageable for the people who work there and will ensure that production can be simultaneously attractive, sustainable in an urban environment and profitable.

- The smart products in Industrie 4.0 are uniquely identifiable and may be located at all times. Even while they are being made, they will know the details of their own manufacturing process. This means that, in certain sectors, smart products will be able to control the individual stages of their production semi-autonomously. Moreover, it will be possible to ensure that finished goods know the parameters within which they can function optimally and are able to recognise signs of wear and tear throughout their life cycle. This information can be pooled in order to optimise the smart factory in terms of logistics, deployment and maintenance and for integration with business management applications.
- In the future under Industrie 4.0, it will be possible to incorporate individual customer- and product-specific features into the design, configuration, ordering, planning, production, operation and recycling phases. It will even be possible to incorporate last-minute requests for changes immediately before or even during manufacturing and potentially also during operation. This will make it possible to manufacture one-off items and very small quantities of goods profitably.
- Implementation of the Industrie 4.0 vision will enable employees to control, regulate and configure smart manufacturing resource networks and manufacturing steps based on situation- and context-sensitive targets. Employees will be freed up from having to perform routine tasks, enabling them to focus on creative, value-added activities. They will thus retain a key role, particularly in terms of quality assurance. At the same time, flexible working conditions will enable greater compatibility between their work and their personal needs.

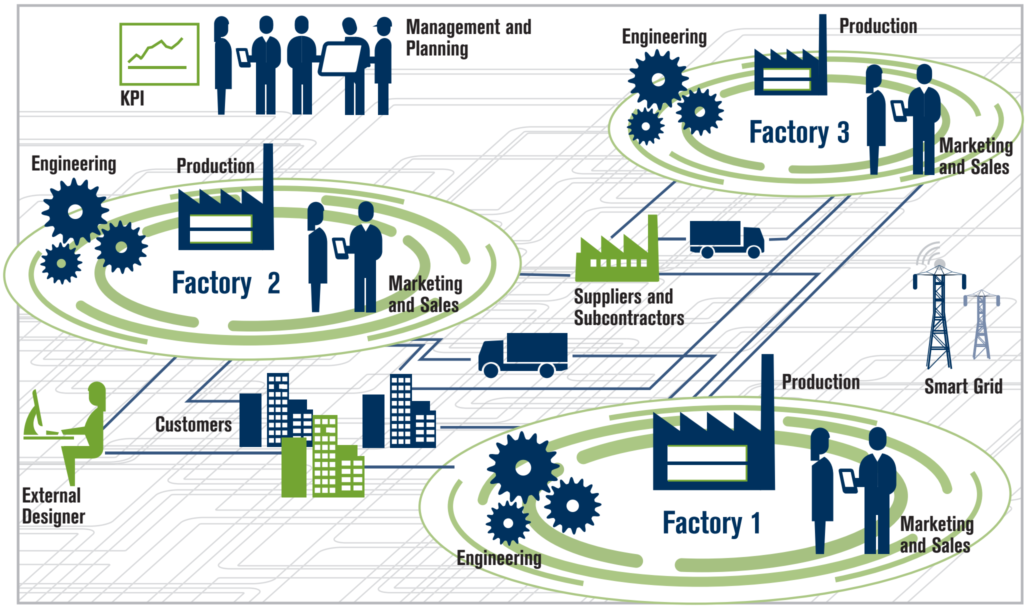
- Implementation of the vision for Industrie 4.0 will require further expansion of the relevant network infrastructure and specification of network service quality through service level agreements. This will make it possible to meet the need for high bandwidths for data-intensive applications and for service providers to guarantee run times for time-critical applications.

2.3 Novel business opportunities and models

Industrie 4.0 will lead to the development of new business and partnership models that are far more geared towards meeting individual, last-minute customer requirements. These models will also enable SMEs to use services and software systems that they are unable to afford under current licensing and business models. The new business models will provide solutions to issues such as dynamic pricing that takes account of customers' and competitors' situations and issues relating to the quality of service level agreements (SLAs) in a context characterised by networking and cooperation between business partners. They will strive to ensure that the potential business benefits are shared fairly among all the stakeholders in the value chain, including the new ones. Broader regulatory requirements such as cutting CO_2 emissions (see Chapter 5.8) can and should be integrated into these business models so that they can be met collectively by the partners in the business networks (see Fig. 3).

Industrie 4.0 use case scenarios relating e.g. to "networked manufacturing", "self-organising adaptive logistics" and "customer-integrated engineering" will require business models that will primarily be implemented by what could be a highly dynamic network of businesses rather than by a single company. This will raise a number of questions regarding financing, development, reliability, risk, liability and IP and know-how protection. As far as the organisation of the network and the qualified differentiation of its services is concerned, it will be crucial to ensure that responsibilities are correctly assigned within the business network, backed up by the relevant binding documentation.
Detailed monitoring of the business models in real time[3] will also play a key role in documenting processing steps and system statuses to demonstrate that the contractual and regulatory conditions have been com-

Figure 3:
Horizontal value network



Source: Hewlett-Packard 2013

plied with. The individual steps of the business processes will be tracked at all times, providing documentary evidence of their completion (see also 5.7). In order to ensure efficient provision of individual services, it will be necessary to establish exactly what the relevant service life cycle might look like, which promises can be guaranteed and which licence models and conditions would allow new partners – especially SMEs – to join the business networks.

In view of the above, it is likely that Industrie 4.0 will give rise to unpredictable global effects and a highly dynamic environment. The disruptive nature of new technologies and their impact on legal issues (e.g. with regard to technology, sensitive corporate data, liability, data protection, trade restrictions, use of cryptography, etc) can pose a threat to the enforceability of existing legislation. Short innovation cycles result in the need for constant updating of the regulatory framework and cause chronic failings in terms of enforcement. It will therefore be necessary to adopt a new approach whereby technologies are tested for their compatibility with the law both prior to and during their development (see Chapter 5.7). Another factor that is key to the success of the Industrie 4.0 initiative is the topic of safety and security (see Chapter 5.4). Once again, a far more proactive approach will be required in this area. Furthermore, it will be important to ensure that the concept of Security by Design is not simply confined to functional components.

2.4 New social infrastructures in the workplace

Industrie 4.0 will bring a number of innovations to a country that is in the throes of demographic change – Germany has the second oldest population in the world, after Japan, whilst the average age of the workforce at many German manufacturing companies is in the mid-forties. The number of young employees is in constant decline and there is already a shortage of skilled labour and applicants for apprenticeships in certain professions. In order to ensure that demographic change does not occur at the expense of current living standards, it will be necessary for Germany to make better use of its existing labour market reserves for Industrie 4.0 whilst at the same time maintaining and improving the productivity of the workforce. It will be especially important to increase the proportion of older people and women in employment. The latest research indicates that individual productivity does not depend on a person's age but is instead connected with the amount of time they have been in a particular position, the way that their work is organised and their working environment. If productivity is to be maintained and increased over the course of longer working lives, it will therefore be necessary to coordinate and transform several different aspects of the workplace, including health management and work organisation, lifelong learning and career path models, team structures and knowledge management.[4] This is a challenge that will have to be met not just by businesses but in particular also by the education system.

Thus, it will not only be new technical, business and legal factors that determine Germany's future competitiveness, it will also be the **new social infrastructures in the Industrie 4.0** workplace that have the capacity to achieve far greater structural involvement of workers in the innovation process.

An important role will also be played by the **paradigm shift in human-technology and human-environment interaction** brought about by Industrie 4.0, with novel forms of collaborative factory work that can be performed outside of the factory in virtual, mobile workplaces. Employees will be supported in their work by smart assistance systems with multimodal, user-friendly user interfaces.

In addition to comprehensive training and CPD measures, work organisation and design models will be key to enabling a successful transition that is welcomed by the workforce. These models should combine a high degree of self-regulated autonomy with decentralised leadership and management approaches. Employees should have greater freedom to make their own decisions, become more actively engaged and regulate their own workload.

The **socio-technical approach of the Industrie 4.0 initiative** will unlock new potential for developing urgently needed innovations, based on a greater awareness of the importance of human work in the innovation process.

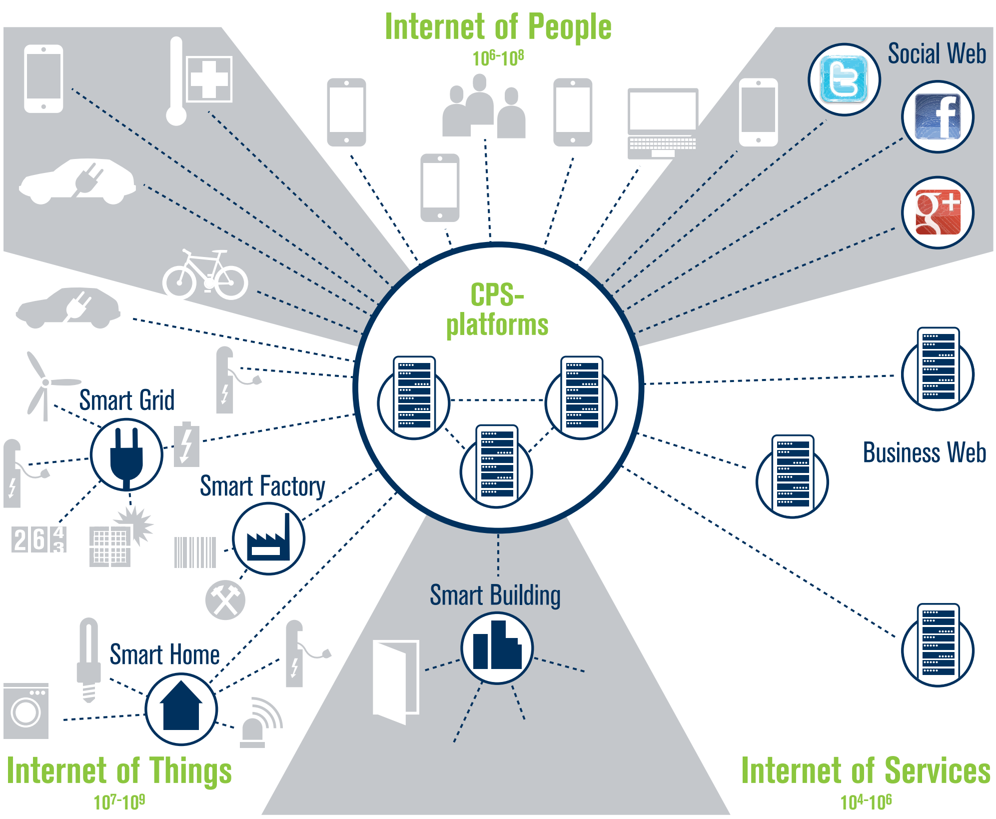
2.5 Novel service-based, real-time enabled CPS platforms

The strategic initiative Industrie 4.0 will give rise to novel CPS platforms geared towards supporting collaborative industrial business processes and the associated business networks for all aspects of smart factories and smart product life cycles.
The services and applications provided by these platforms will connect people, objects and systems to each other (see Fig. 4) and will possess the following features:

- Flexibility provided by rapid and simple orchestration of services and applications, including CPS-based software
- Simple allocation and deployment of business processes along the lines of the App Stores model
- Comprehensive, secure and reliable backup of the entire business process
- Safety, security and reliability for everything from sensors to user interfaces
- Support for mobile end devices
- Support for collaborative manufacturing, service, analysis and forecasting processes in business networks.

In the context of the business networks, there is a particular need for IT development work with regard to the orchestration of services and applications on shared CPS platforms, since this is where the specific requirements for horizontal and vertical integration of CPS, applications and services arise in industrial business processes (see also Chapter 5.1). For Industrie 4.0, it is important to interpret the term 'orchestration' more broadly than is usually the case in the context of web services. It should explicitly include the setting up of shared services and applications in collaborative inter-company processes and business networks. Issues such as safety and security, confidence, reliability, usage, operator model convergence, real-time analysis and forecasting will all need to be reviewed for the orchestration and subsequent effi-

Figure 4:
The Internet of Things and Services – Networking people, objects and systems



Source: Bosch Software Innovations 2012

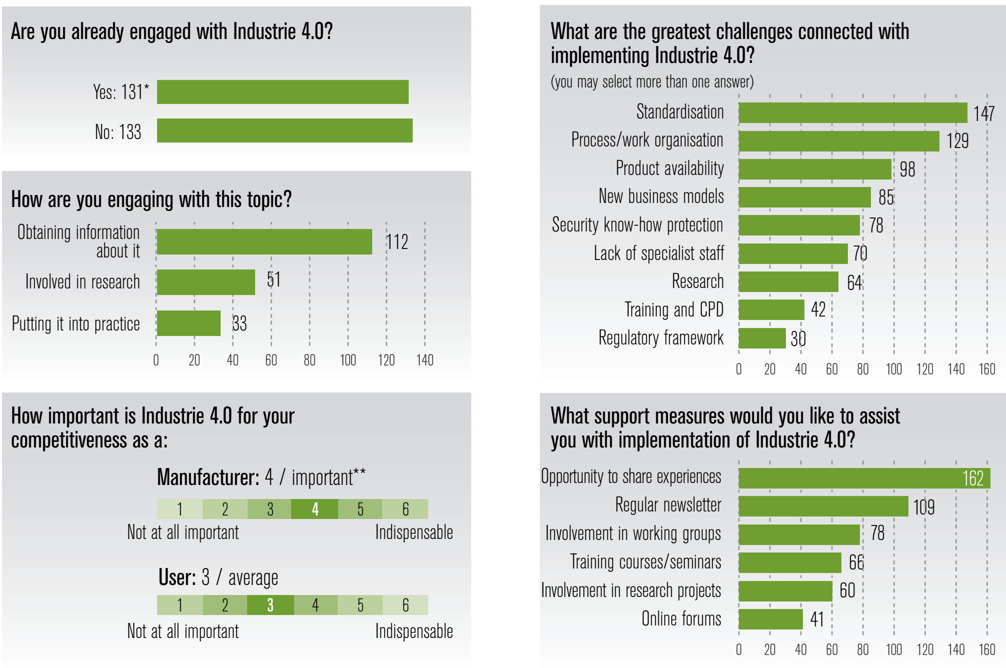
cient, reliable, safe and secure operation of collaborative manufacturing and service processes as well as for the execution of dynamic business processes on CPS platforms. Among other things, this will involve addressing the challenges posed by the wide range of different data sources and end devices. The requirements referred to above are currently met in only a very rudimentary fashion by generic cloud infrastructure initiatives. Inter-company use of CPS platforms by IT, software and service providers and by the users themselves will require an Industrie 4.0 reference architecture that will need to take account of the different perspectives of the ICT and manufacturing industries (see Chapter 5.1). Modelled methods will be required to develop new applications and services for these CPS platforms, in order to manage the complexity resulting from increasing functionality, customisation, dynamism and cooperation between different disciplines and organisations (see Chapter 5.2).

Availability of a secure and efficient network infrastructure with high bandwidths will be key to guaranteeing the necessary secure data exchange (see Chapter 5.3).

2.6 The road to Industrie 4.0

Implementing the vision of Industrie 4.0 will involve an evolutionary process that will progress at different rates in individual companies and sectors. A survey on the "prospects for Industrie 4.0" carried out at the beginning of the year by the professional associations BITKOM, VDMA and ZVEI confirmed the importance of this topic for the competitiveness of German industry and documented the need for fuller and more targeted information (see Fig. 5). Some 47 percent of the companies in the survey[5] said that they were already actively engaged with Industrie 4.0. 18 percent of these companies said that they were involved in research into Industrie 4.0, whilst 12 percent claimed that they were already putting it into practice.

Figure 5:
Results of survey on Industrie 4.0 trends (January 2013)



278 companies took part in the survey, mainly from the machinery and plant manufacturing industry. 205 of the companies that took part had fewer than 500 employees.

* The figures refer to the number of companies ** Average score based on answers provided by all companies Source: BITKOM, VDMA, ZVEI 2013

The three greatest challenges connected with implementing the vision were identified as standardisation, work organisation and product availability.
Alongside active involvement in working groups, other support measures requested by companies to aid them with implementation of Industrie 4.0 include targeted seminars where they can share experiences and regular newsletters. The professional associations will play an important role in ensuring a steady flow of communication, working closely with the social partners, the academic community and the public. Approximately 50 percent of the companies surveyed said that they had already received information about Industrie 4.0 through their professional associations.
In addition to the above, the Working Group considers the following measures to be key to enabling a smooth transition to Industrie 4.0 for businesses:

- Implementation of real-time enabled CPS solutions will place high demands on the availability of services and network infrastructure in terms of space, technical quality and reliability. In order to secure Germany's competitiveness internationally, harmonisation of services and business models through the introduction of the relevant international standards should be supported by policymakers both nationally and globally (see also Chapters 5.1 and 5.3).
- Business processes in manufacturing are currently often still static and implemented through extremely inflexible software systems. However, they cannot simply be replaced overnight by service-oriented systems. It will be essential to integrate new technologies into older ones (or vice versa) – old systems will need to be upgraded with real-time enabled systems.
- The rate of development of new business models for manufacturing in the Internet of Things and Services will approach the rate of development and dynamism of the Internet itself.
- Employees will be involved at an early stage in the innovative socio-technical design of work organisation, CPD and technological development (see Chapter 5.5).
- In order to achieve the transition to Industrie 4.0, it will be necessary for the ICT industry (that is accustomed to short innovation cycles) to work closely with machinery and plant manufacturers and mechatronic system suppliers (who tend to think in terms of much longer innovation cycles) in order to develop business models that are acceptable to all the partners.

TAKE-HOME MESSAGE:
In conjunction with smart production, smart logistics, smart grids and smart products, the increasing use of the Internet of Things and Services in manufacturing will transform value chains and lead to the emergence of new business models.
The strategic initiative Industrie 4.0 will leverage the existing technological and commercial potential. Industrie 4.0 offers the prospect of new business opportunities and innovative new social infrastructures in the workplace.

1 In 2009, the Industry-Science Research Alliance identified five key areas for action: climate/energy, mobility, health, security and communication; more information online at: www.forschungsunion.de.

2 Since the 3rd industrial revolution, ICT has not only been used in manufacturing in order to optimise costs and efficiency, but also in processes that touch on or overlap with manufacturing such as logistics, diagnostics, quality assurance, maintenance, energy management or human resource planning. However, the different IT systems have developed separately over time and the separate evolution and predominantly closed nature of their architectures means that technically it would be extremely complex to integrate them. This makes it exceptionally difficult to achieve comprehensive networking of IT systems and flexible reconfiguration of manufacturing systems, meaning that it is often simply not possible to take advantage of the potential offered by this approach. In Industrie 4.0, these restrictions will no longer apply.

3 "Real time" refers to data processing that occurs synchronously with events in the real world, as opposed to data processing where a delay is involved.

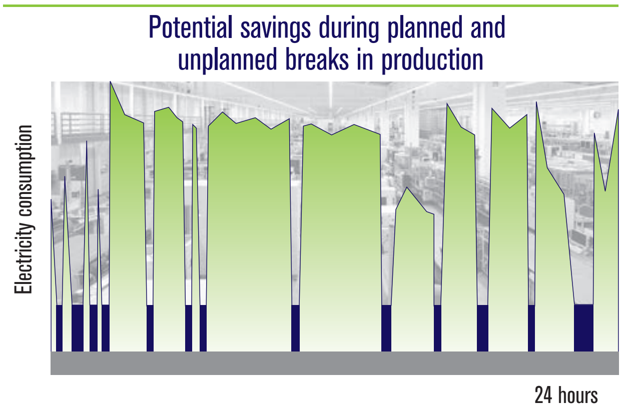
4 See Altern in Deutschland, Vol. 9: Gewonnene Jahre, Empfehlungen der Akademiengruppe, Nova Acta leopoldina NF No. 371, Vol. 107, Stuttgart 2009, p. 49, 56. Immigrants and low-skilled workers (if they receive further training) also constitute sources of untapped potential for the labour market, see OECD: Zuwanderung ausländischer Arbeitskräfte: Deutschland, 2013, available online at: http://www.oecd-ilibrary.org/social-issues-migration-health/zuwanderung-auslandischer-arbeitskrafte-deutschland-german-version_9789264191747-de

5 278 companies participated in the survey, Source: BITKOM, VDMA and ZVEI, January 2013.

EXAMPLE APPLICATION 1: Reducing the energy consumed by a vehicle body assembly line while it is not in use

Today, energy efficiency is already an important requirement for machinery. A key enabler for meeting this requirement is the ability to systematically power down inactive parts of a line during breaks in production. Industrie 4.0 will make greater use of the opportunities that exist to do this by ensuring that this capability is consistently integrated into the planning and operation of production facilities.

Today

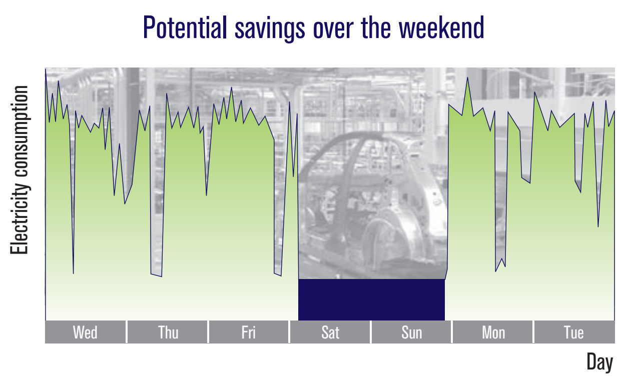


Source: Siemens 2013

Currently, many production lines or parts thereof continue running and consuming high quantities of energy during breaks, weekends and shifts where there is no production. For example, **12 percent of the total energy consumption** of a vehicle body assembly line that uses laser welding technology occurs during breaks in production. The line operates five days a week on a three shift pattern. Although this complex piece of machinery is not in use over the weekend, it remains powered up so that it can resume production immediately once the weekend is over.

90 percent of power consumption during breaks in production is accounted for by the following: robots (20 to 30 percent), extractors (35 to 100 percent) and laser sources and their cooling systems (0 to 50 percent).

Tomorrow



Quelle: Siemens 2013

Measures to leverage energy efficiency potential:
In the future, **robots** will be powered down as a matter of course even during short breaks in production. During longer breaks in production they will enter a kind of standby mode known as Wake-On-LAN mode.[1] The extractors will use **speed-controlled motors that can be adjusted to meet requirements** instead of motors that cannot be controlled in this way. In the case of the **laser sources**, completely new systems are the only way of delivering improvements.

Taken together, these measures enable a reduction of **12 percent of total energy consumption** to be achieved (from 45,000kWh/w to approx. 40,000kWh/w), together with a **90 percent cut in energy consumption** during breaks in production. These energy efficiency considerations should be taken into account right from the earliest stages when designing CPS.

1 The robots are controlled using PROFIenergy

POTENTIAL BENEFITS

Coordinated power-up and power-down of parts of a vehicle body assembly line leads to improved energy efficiency. Whilst the cost/risk ratio and cost-effectiveness of upgrading existing machinery are not very attractive, this approach will become an established technical standard for the new machines that will be developed by Industrie 4.0's leading suppliers, enabling improved energy efficiency to be achieved.

3 The dual strategy: becoming a leading market and supplier

3 The dual strategy: becoming a leading market and supplier

The fourth industrial revolution (Industrie 4.0) holds huge potential for manufacturing industry in Germany. Increased deployment of CPS in German factories will strengthen German manufacturing industry by improving the efficiency of domestic production. At the same time, the development of CPS technology offers significant opportunities for exporting technologies and products. Consequently, the implementation of the Industrie 4.0 initiative should aim to leverage the market potential for German manufacturing industry[1] through the adoption of a **dual strategy** comprising the **deployment of CPS** in manufacturing on the one hand and the **marketing of CPS technology and products** in order to strengthen Germany's manufacturing equipment industry on the other.

3.1 Leading supplier strategy

The leading supplier strategy addresses the potential of Industrie 4.0 from the point of view of the equipment supplier industry . German equipment suppliers provide manufacturing industry with world-leading technological solutions and are thus in pole position to become global leaders in the development, production and worldwide marketing of Industrie 4.0 products. The key is now to find smart ways of combining outstanding technological solutions with the new potential offered by information technology, in order to achieve a **quantum leap in innovation.** It is this systematic combination of information and communication technology with traditional high-tech strategies that will enable rapidly changing markets and increasingly complex global market processes to be managed so that companies can carve out new market opportunities for themselves.

- **Existing basic IT technologies** need to be **adapted to the specific requirements of manufacturing** and **continue to be developed with this particular application in mind.** In order to achieve economies of scale and ensure widespread effectiveness, it will be necessary to enhance the manufacturing technology and IT systems of existing facilities with CPS capabilities as part of the strategy for migrating to Industrie 4.0. At the same time, it will be necessary to develop models and strategies for designing and implementing CPS manufacturing structures at new sites.
- If Germany wishes to achieve its goal of lasting leadership as a supplier of Industrie 4.0 equipment, **research, technology and training initiatives** should be promoted **as a matter of priority** with a view to developing methodologies and pilot applications in the field of automation engineering modelling and system optimisation (see Chapter 5.2).
- Another key challenge will be to **use the technology to create novel value networks. This will involve developing new business models**, particularly ones that link products with the appropriate services.

3.2 Leading market strategy

The leading market for Industrie 4.0 is Germany's domestic manufacturing industry. In order to shape and successfully expand this leading market, close networking of parts of businesses located at different sites will be required, together with closer cooperation between different enterprises. This will in turn require logical, end-to-end digital integration of the different value creation stages and the life cycles of products, product ranges and the corresponding manufacturing systems. One particular challenge will be to achieve **simultaneous integration into these emerging new value networks of both large-scale undertakings that already operate globally today and SMEs that often still operate only at a regional level.** The strength of Germany's manufacturing industry is in no small measure due to a balanced structure comprising a large number of small and medium-sized enterprises and a smaller number of large-scale undertakings. However, many SMEs are not prepared for the structural changes that Industrie 4.0 will entail, either because they lack the requisite specialist staff or because of a cautious or even sceptical attitude towards a technology strategy that they are still unfamiliar with.

» Germany's economy is characterised by its strong industrial base, particularly its machinery and plant manufacturing, automotive and energy industries. Implementation of Industrie 4.0 will be absolutely key to its future development – we cannot allow industry to come to a standstill. «

Ernst Burgbacher
Parliamentary State Secretary
Federal Ministry of Economics and Technology

One key strategy for integrating SMEs into global value networks is therefore **the design and implementation of a comprehensive knowledge and technology transfer initiative.** For example, pilot applications and best practice examples of networks of large-scale industrial undertakings and SMEs could help to make the potential of networked value chains more visible and convince small and medium-sized enterprises to adopt the methodological and organisational tools and technologies of the leading suppliers. This would remove the barriers to SMEs becoming acquainted with CPS methodologies, taking them on board and implementing them in their own businesses.

In order to make this possible, it will be essential to accelerate the use and development of the technological infrastructure, including high-speed broadband data transmission (see Chapter 5.3). In parallel, it will also be important to educate and train skilled workers (see Chapter 5.6) whilst simultaneously developing customised and efficient organisational designs for complex working arrangements (see Chapter 5.5).

3.3 The dual strategy and its key features

Optimal delivery of Industrie 4.0's goals will only be possible if the leading supplier and leading market strategies are coordinated to ensure that their potential benefits complement each other. Hereafter, this approach will be referred to as the **dual strategy**. The strategy incorporates three key features (see also Chapter 2.1):

- Development of inter-company value chains and networks through horizontal integration
- **Digital end-to-end engineering** across the entire value chain of both the product and the associated manufacturing system
- Development, implementation and vertical integration of flexible and reconfigurable manufacturing systems within businesses

These features are the key enablers for manufacturers to achieve a stable position in the face of highly volatile markets whilst flexibly adapting their value creation activities in response to changing market requirements. The features outlined under this dual CPS strategy will allow manufacturing companies to achieve rapid, on-time, fault-free production at market prices in the context of a highly dynamic market.

3.3.1 Horizontal integration through value networks

Models, designs and implementations of horizontal integration through value networks should provide answers to the following key question:

How can companies' business strategies, new value networks and new business models be sustainably supported and implemented using CPS?

This question applies in equal measure to the realms of research, development and application (see Fig. 6). In addition to "business models" and "forms of cooperation between different companies", it is also necessary to address topics such as "sustainability", "know-how protection", "standardisation strategies" and "medium to long-term training and staff development initiatives".

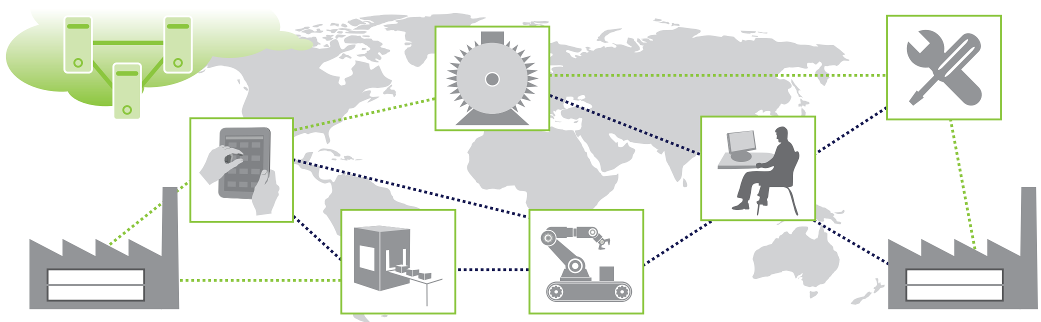
3.3.2 End-to-end engineering across the entire value chain

The following key question arises in connection with the goal of achieving end-to-end digital integration throughout the engineering process so that the digital and real worlds are integrated across a product's entire value chain and across different companies whilst also incorporating customer requirements:

How can CPS be used to deliver end-to-end business processes including the engineering workflow?

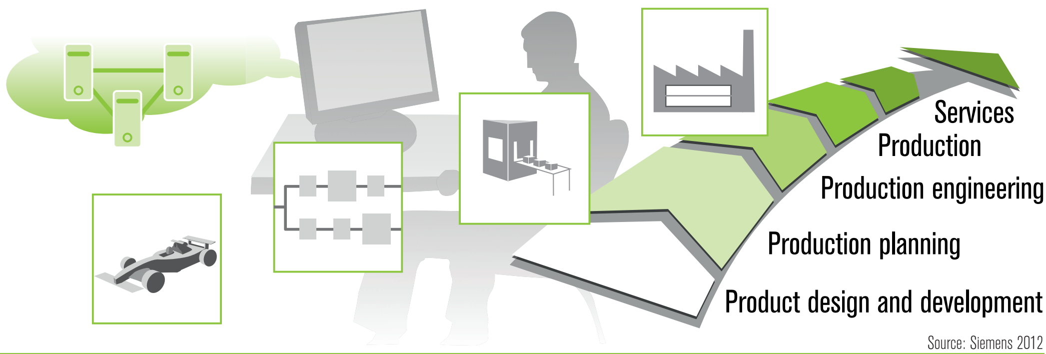
In this regard, modelling plays a key role in managing the increasing complexity of technological systems (see Chapter 5.2). The appropriate IT systems should be deployed in order to provide end-to-end support to the entire value chain, from product development to manufacturing system engineering, production and service (see Fig. 7). A holistic systems engineering approach is required that spans the different technical disciplines. For this to be possible, engineers will need to receive the appropriate training.

Figure 6:
Horizontal integration through value networks



Source: Siemens 2012

Figure 7:
End-to-end engineering across the entire value chain



Source: Siemens 2012

3.3.3 Vertical integration and networked manufacturing systems

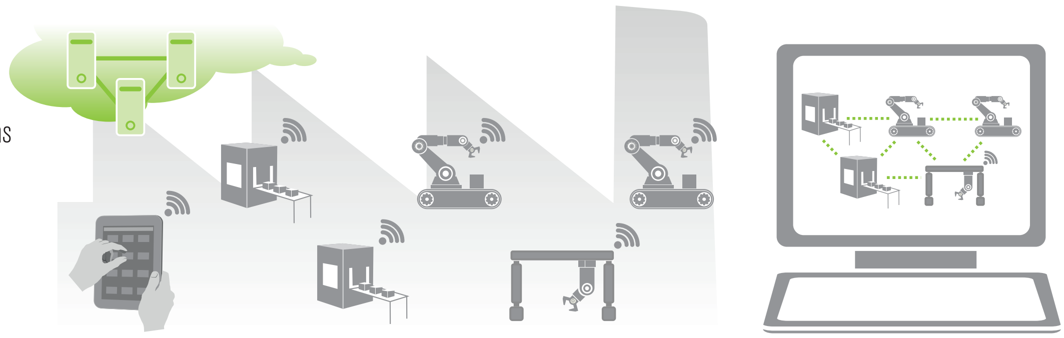
As far as vertical integration is concerned, the following key question needs to be answered:

How can CPS be used to create flexible and reconfigurable manufacturing systems?

The setting for vertical integration is the factory. In tomorrow's smart factories, manufacturing structures will not be fixed and predefined. Instead, a set of IT configuration rules will be defined that can be used on a case-by-case basis to automatically build a specific structure (topology) for every situation, including all the associated requirements in terms of models, data, communication and algorithms (see Fig. 8).

In order to deliver vertical integration, it is essential to ensure end-to-end digital integration of actuator and sensor signals across different levels right up to the ERP level. It will also be necessary to develop modularisation and reuse strategies in order to enable ad hoc networking and reconfigurability of manufacturing systems, together with the appropriate smart system capability descriptions. Moreover, foremen and operators will need to be trained to understand the impact of these approaches on the running and operation of the manufacturing system.

Figure 8: Vertical integration and networked manufacturing systems



Source: Siemens 2012

TAKE-HOME MESSAGE:

Industrie 4.0 can serve to create **horizontal value networks** at a strategic level, provide **end-to-end integration across the entire value chain** of the business process level, including **engineering**, and enable **vertically integrated** and **networked** design of **manufacturing systems**.

Implementation of the strategic initiative Industrie 4.0 – both in terms of research funding and concrete development and implementation measures – should therefore be based on a **dual strategy** geared towards delivering the twin goals of creating a **leading market** among Germany's manufacturing companies and making Germany's manufacturing equipment industry into a **leading supplier**.

1 Manufacturing industry includes all companies that manufacture (or have someone else manufacture) a physical product in a manufacturing system by processing raw materials and semi-finished products. This includes both machining and process-based processing.

2 The equipment supplier industry includes machinery and plant manufacturers, suppliers of automation products, systems and solutions and software companies that supply e.g. Product Lifecycle Management (PLM) systems, manufacturing or logistics software applications or business planning software systems.

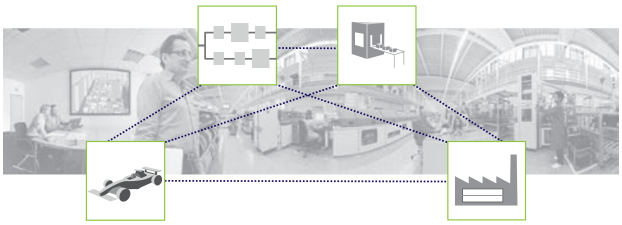
3 Topology refers to the way that a manufacturing system is configured using manufacturing resources (e.g. machines, jobs, logistics) and the associated interactions (e.g. material flow).

EXAMPLE APPLICATION 2: End-to-end system engineering across the entire value chain

Benefits: End-to-end digital system engineering and the resulting value chain optimisation will mean that customers no longer have to choose from a predefined range of products specified by the manufacturer but will instead be able to mix and match individual functions and components to meet their specific needs.

Today

A variety of interfaces between IT support systems

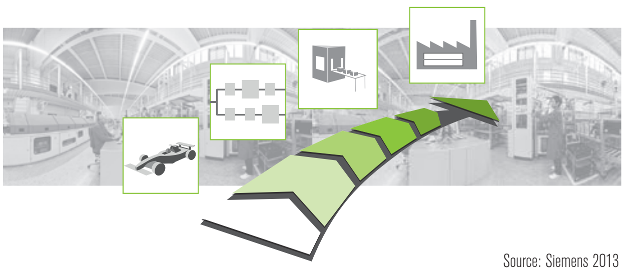


Source: Siemens 2013

Today's value chains – from customer requirements to product architectures and production – have often arisen over a period of many years and tend to be relatively static. IT support systems exchange information via a variety of interfaces, but can only use this information with regard to specific individual cases. **There is no global overview from the perspective of the product that is being manufactured.** As a result, customers cannot freely select all of their product's functions and features, even though technically it would be possible to allow them to do so. For example, it is possible to order a rear windscreen wiper for an estate car, but not for a limousine made by the same company. Furthermore, IT system maintenance costs are currently still very high.

Tomorrow

End-to-end system engineering across the entire value chain



Source: Siemens 2013

The model-based development enabled through CPS allows the deployment of an end-to-end, modelled, digital methodology that covers every aspect from customer requirements to product architecture and manufacture of the finished product. This enables all the interdependencies to be identified and depicted in an **end-to-end engineering** tool chain. The manufacturing system is developed in parallel based on the same paradigms, meaning that it always keeps pace with product development. **As a result**, it becomes feasible to manufacture individual products.

It is possible to preserve the value of the current installed base by migrating to this tool chain gradually over a number of stages.

POTENTIAL BENEFITS

1. Higher sales thanks to a larger market and higher customer satisfaction.
2. Reduction of internal operating costs through digital end-to-end integration of the value chain.

4 Research requirements

4 Research requirements

Although Industrie 4.0 will largely be implemented by industry itself, there is still a fundamental need for further research. The Industrie 4.0 Working Group identified and presented the main medium- and long-term research requirements and actions in October 2012. These are summarised in the following section.

The main aim of Industrie 4.0 is to implement a **dual strategy** (see Chapter 3) based on coordination of the **leading supplier** and **leading market** strategies. This should be supported by research activities. In Industrie 4.0, it is expected that the revolutionary applications will come about principally as a result of combining ICT with manufacturing and automation technology.

For this to happen, existing CPS features will need to be adapted in the medium term for deployment in manufacturing systems. This will require machine and plant manufacturers' strengths as integrators to be pooled with the competencies of the ICT and automation industries to establish targeted, creative development processes for creating new CPS. The new level of networking required to achieve end-to-end integration of product models, manufacturing resources and manufacturing systems is going to necessitate a huge research and development effort in the longer term.

The priority for future research is shifting towards the investigation and development of fully describable, manageable, context-sensitive and controllable or self-regulating manufacturing systems.

In the long term, these will consist of functional CPS components drawn from cross-discipline, modular toolkits that can either be configured using help functions or integrate themselves synergistically into an existing infrastructure during production. It should also be possible to achieve significantly enhanced integration of virtually planned and real manufacturing processes. **In the long term, it will therefore be necessary for researchers to develop modular CPS and the corresponding component catalogues as a key feature of any model smart factory.**

A quantum leap in innovation will only be achieved if existing basic technologies are developed in an applied manner to meet the specific requirements of the manufacturing environment. The resulting methods, approaches and best practice examples will need to be disseminated across the different levels of the value networks in order to achieve **cross-discipline knowledge and technology transfer.** It is for this reason that the section on the dual strategy (see Chapter 3) has already provided an in-depth look at three of the five central research themes:

1. **Horizontal integration through value networks**
2. **End-to-end engineering across the entire value chain**
3. **Vertical integration and networked manufacturing systems**

In the long term, this technology-driven research centred around manufacturing system applications will result in an increase in inter-company or inter-divisional interdisciplinary cooperation that will act as a strategic enabler for predominantly small and medium-sized machinery and plant manufacturers. This will allow the industry to respond much more swiftly to market requirements and establish itself as the leading supplier of a wide range of new products, services and business models.

However, interdisciplinarity will not come about purely through greater cooperation between engineers and automation engineers. The significant impact of the fourth industrial revolution on the industrial jobs of tomorrow is something that will have to be addressed both through research and at a practical level. This brings us to the fourth research requirement:

4. New social infrastructures in the workplace

In the interests of social responsibility, it will be necessary to increase the involvement and promote the engagement of employees in terms of using their skills and experience with regard to both creative design and planning processes as well as in the operational working environment. CPS will therefore require new work organisation structures covering the entire value network in order to boost employees' productivity and provide organisational structures that support individuals' lifelong development.

» Through Industrie 4.0 we will also be enabling a paradigm shift in human-technology interaction. It will be machines that adapt to the needs of human beings and not vice versa. Smart industrial assistance systems with multimodal user interfaces will bring digital learning technologies directly into the workplace «

Prof. Dr rer. nat. Dr h. c. mult. Wolfgang Wahlster
CEO of the German Research Center for Artificial Intelligence (DFKI GmbH)
Member of the Communication Promoters Group of the Industry-Science Research Alliance

An interdisciplinary approach should be adopted to these issues, drawing on the expertise of a team comprising engineers, IT experts, psychologists, ergonomists, social and occupational scientists, doctors and designers.

The basic overview presented above indicates that practical methods and basic technologies to enable collaborative work in the realm of manufacturing and automation engineering are currently still widely unavailable in many areas.

In order to ensure that they can be used in different companies and industries with different IT systems, technical resources and competencies, the basic ICT technologies need to be adapted to the requirements of automation engineering. A further key to success will be the establishment of practical reference architectures. Among other things, this aspect relates to the need to establish service-based, real-time enabled infrastructures as (or belonging to) ICT platforms for vertical and horizontal integration as already touched upon in Chapter 2. These infrastructures will need to be standardised so that they can be used by different companies and technologically orchestrated in order to enable the widespread creation of shared business networks through the establishment of the appropriate web services.

This brings us to the final area where research and action are still required for Industrie 4.0:

5. Cyber-Physical Systems technology

The consolidated research requirements have been broken down into the five research areas described in this section. The feedback received through the Industrie 4.0 Working Group, including contributions from the business and research communities, builds on the recommendations of the Communication Promoters Group that were submitted to the Industry-Science Research Alliance in two reports in January and September 2011. It remains desirable to implement these recommendations, together with the outcomes of the BMBF-sponsored project "Integrated Research Agenda Cyber-Physical Systems"[1] and the BMWi study "*Das wirtschaftliche Potential des Internets der Dienste*" (The Economic Potential of the Internet of Services). Consequently, they should be understood as referring to the need to adapt basic ICT technologies to the requirements of automation and manufacturing engineering, including the continuation of efforts to address general research requirements in this regard. They should also be regarded as a concrete description of the actions required in order to implement the vision described above for the specific application of "industrial engineering".

In order to provide ideas and guidance for the make-up of the relevant funding programmes, the Industrie 4.0 Working Group has furthermore identified **the key actions and research requirements for the medium to long term.**

TAKE-HOME MESSAGE:

An intensive dialogue between the relevant ministries and the Industrie 4.0 Platform will be required in order to put together a comprehensive funding package for industry and the research community. The Industrie 4.0 Platform should ensure that its Industrial Steering Committee and Scientific Advisory Committee include experts from the realms of manufacturing, automation and IT, legal and management experts and social scientists. The Industrie 4.0 Platform's Working Groups should invite additional experts from the research and business communities to assist with the immediate task of drawing up comprehensive R&D roadmaps that adapt the consolidated research recommendations to the specific requirements of each working group.

In addition to facilitating discussions and informal exchanges within the Industrie 4.0 community, the Industrie 4.0 Platform should also identify potential synergies between the various projects and partnerships that are currently in existence.

1 See research recommendations for CPS in manufacturing: "The deployment of Cyber-Physical Systems in manufacturing systems creates smart factories whose products, resources and processes are all characterised by Cyber-Physical Systems. Their specific qualities offer advantages over conventional manufacturing systems with regard to quality, time and costs. As part of the "Industrie 4.0" initiative launched in 2011, we recommend the establishment of a project geared towards removing technological and economic barriers and accelerating the implementation and deployment of smart factories." Quotation from: acatech (Ed.): Cyber-Physical Systems. Innovationsmotor für Mobilität, Gesundheit, Energie und Produktion (Cyber-Physical Systems. Driving force for innovation in mobility, health, energy and production) (acatech POSITION PAPER), Heidelberg et al.: Springer Verlag 2011, p. 35.

5 Priority areas for action

5 Priority areas for action

Industrie 4.0 is a complex initiative that embraces several partially overlapping areas. In October 2012, the Industrie 4.0 Working Group presented a comprehensive collection of medium- and long-term **research recommendations.** The following sections focus on the key **priority areas** where the Working Group believes that there is a need for concrete industrial policy and business decisions to be taken in order for the recommendations to be implemented. The Industrie 4.0 Platform was established in order to shape the implementation process.

5.1 Standardisation and open standards for a reference architecture

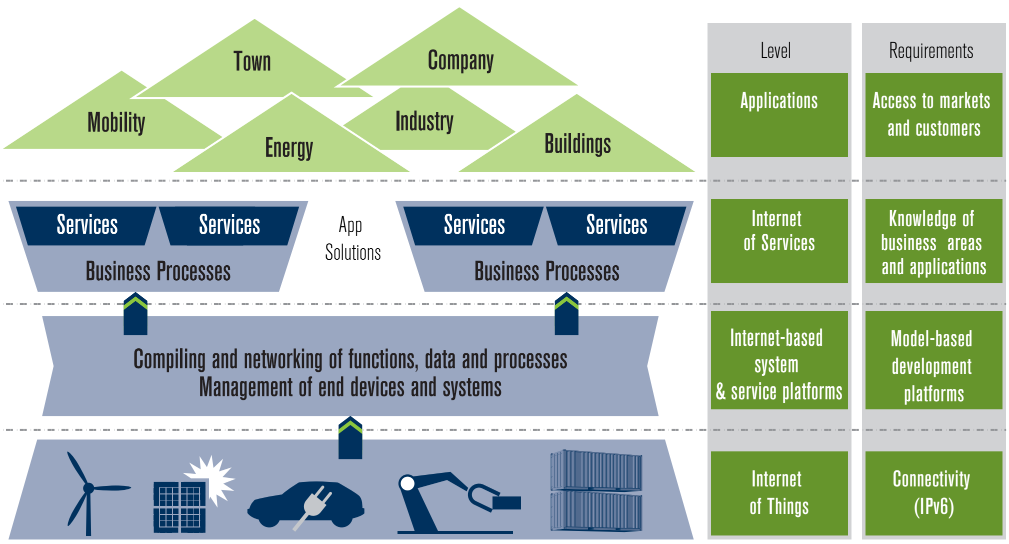
If Industrie 4.0 is to enable inter-company networking and integration through value networks (see Chapter 3), the appropriate standards will need to be developed. Standardisation efforts will need to focus on stipulating the cooperation mechanisms and the information that is to be exchanged. The complete technical description and implementation of these provisions is referred to as the **reference architecture**.

The reference architecture is thus a general model that applies to the products and services of all the partner companies. It provides a framework for the structuring, development, integration and operation of the technological systems relevant to Industrie 4.0. It is provided in the shape of software applications and software services (see e.g. Fig. 9).

Since the value network in Industrie 4.0 comprises several different companies with very different business models, the role of the reference architecture is to pull together these divergent approaches into one **single, common approach**. This will require the partners to agree on the basic structural principles, interfaces and data.
The example of a manufacturing system serves to outline some of the different perspectives that would need to be integrated into a reference architecture (see Fig. 10):

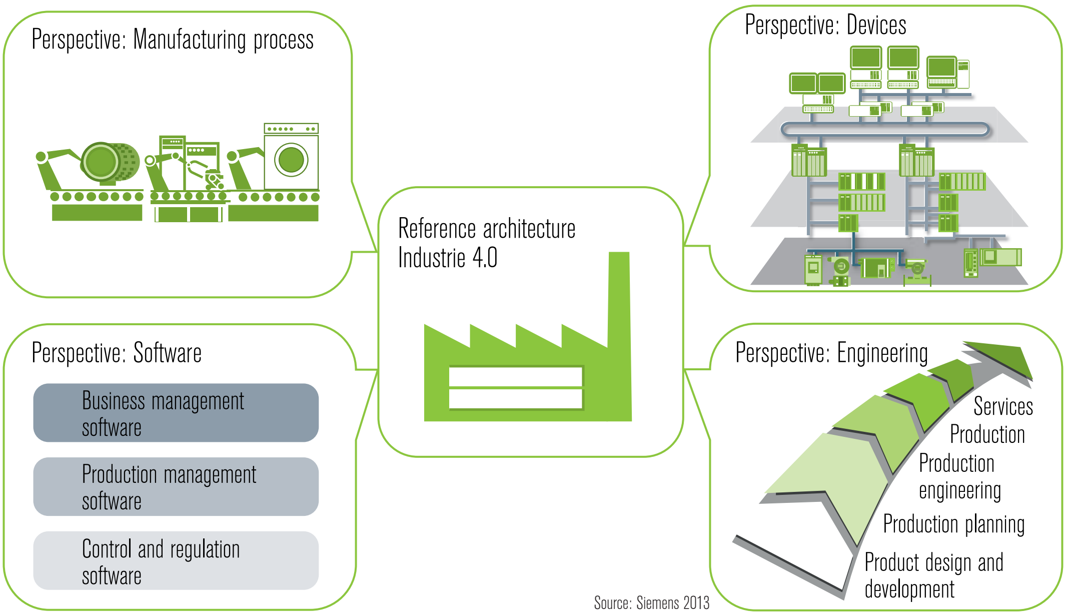
- The perspective of the manufacturing process in terms of processing and transport functions
- The perspective of specific networked devices in a manufacturing system, such as (smart) automation devices, field devices, fieldbuses, programmable logic controllers, operating devices, mobile devices, servers, workstations, Web access devices, etc

Figure 9: Reference architecture for connecting the Internet of Things with the Internet of Services



Source: Bosch Software Innovations 2012

Figure 10: Examples of the different perspectives included in the Industrie 4.0 reference architecture



- The perspective of the software applications in the manufacturing environment, such as data acquisition through sensors, sequential control, continuous control, interlocking, operational data, machine data, process data, archiving, trend analysis, planning and optimisation functions, etc
- The perspective of the software applications used by one or more businesses, e.g. for business planning and management, inter-company logistics or supporting value networks, including the relevant interfaces and integration with the manufacturing environment
- The engineering perspective in a manufacturing system (Product Lifecycle Management/PLM). For example, this could involve using data derived from the manufacturing process to plan the necessary resources (in terms of both machinery and human resources). It would subsequently be possible to successively optimise machines in terms of their mechanical, electrical and automation technology properties, right up to the point where the manufacturing system is set up and brought online, whilst also taking operation and maintenance into account.

Challenges

The first challenge is to pull together the different established ways of seeing things that currently exist in the realms of

- production engineering, mechanical engineering, process engineering,
- automation engineering and
- IT and the Internet

and establish a **common approach.** Since Industrie 4.0 will require cooperation between companies in the machinery and plant manufacturing, automation engineering and software sectors, the first step will be to agree on a **common basic terminology.**
Although several established standards are already in use by the various technical disciplines, professional associations and working groups, a coordinated overview of these standards is currently lacking. It is therefore necessary for **existing standards** e.g. in the field of automation (industrial communication, engineering, modelling, IT security, device integration, digital factories) to be incorporated into a new global reference architecture.

The reference architecture cannot be developed in a top-down manner since it will need to integrate several different perspectives and a top-down approach would in any case take far too long. It therefore makes sense for the reference architecture to be **developed incrementally** and from a variety of starting points. In this regard, it will be necessary for strategies that are currently often implemented in a project-specific manner based on local circumstances to be gradually converted into an **international standard**. In doing so, it will be important to ensure that interfaces remain technically stable for many years to come and to preserve the value of the installed base. On the Internet, the approach to standardisation is based on different **paradigms** to those that are currently the norm in the machinery and plant manufacturing industry, for example

- *Open operating systems:* in the case of Linux, a community of businesses, research institutions and individuals comprising more than 2,000 developers in over 100 countries develops and maintains one of the world's most successful operating systems.

- *Open development tools:* a community comprising over 1,500 developers and millions of users develops software for demanding modelling applications.

- *Open communication infrastructure:* "Requests for Comments" are technical and organisational documents published through the Internet Society that were first established as long ago as 07.04.1969. Their widespread acceptance and use has converted them into de facto standards. Well-known examples include the Internet protocol (TCP/IP) and e-mail protocol (SMTP).

These paradigms enable standardisation efforts to be progressed far more rapidly.
Finally, it will be important to build **trust** in the reference architecture. This is particularly relevant with regard to know-how protection (see Chapter 5.7). It will also be key to ensure that the full range of intended users of the reference architecture are appropriately engaged in its design right from the early stages.

Recommended actions

The Industrie 4.0 Working Group recommends the establishment of a **Working Group** under the auspices of the Industrie 4.0 Platform to deal exclusively with the topic of standardisation and a reference architecture. The Working Group's remit would include the following tasks:

- Building a shared understanding of the goals, benefits, potential and risks, possible content and implementation strategies with a view to creating the **mutual confidence** needed to support joint implementation measures. The professional associations should take the lead with regard to the implementation of confidence-building measures.
- Alignment of the key **terminology** and subsequent production of a common "Industrie 4.0 glossary". In addition, detailed attention should to be paid to those aspects of the following issues that are relevant to the specific content of Industrie 4.0:
  - Model universals (underlying core models, reference models, architecture designs)
  - Standards for the Industrie 4.0 service architecture
  - Standards for a supra-automation level procedural and functional description
  - Terminology standards and the use of ontologies
  - Understanding of autonomous and self-organising systems, including their planning, operation and security
  - Characteristics maintenance and system structure description
  - Approach to migrating existing architectures

- Production of a **bottom-up map** outlining the standardisation bodies that currently exist today. Current, established "automation reference architecture" approaches and examples would then be located on the map. This could serve as a basis for assessing the different themes with regard to further development and migration in the context of Industrie 4.0 and identifying clusters of themes that are not currently covered.
- Starting work on the production of a **top-down roadmap**, taking account of cost-benefit considerations and time constraints. A holistic approach should be adopted in order to strike a sensible balance between standardisation and individuality. The structure should be open and transparent and all the stakeholders should be engaged in the development and use of the standards. Licensing models should also be addressed.
- Development of an "**Industrie 4.0 community" with members from several different companies** that feels responsible for the technical implementation of the reference architecture and is able to roll it out and maintain it in the longer term. This will require a suitable licensing model and an appropriate community process to be chosen.
- Other tasks forming part of the Working Group's remit would include moderation, recommendations, evaluation, communication and motivation.

The Working Group also recommends the establishment of appropriate **flagship projects** to demonstrate the successful development and deployment of reference architectures. Figure 11 provides an example of a possible reference architecture focused on horizontal integration through value networks.
Other topics for reference architectures could include end-to-end engineering of products and their associated manufacturing systems or real-time process communication for the management and control of highly dynamic technological manufacturing processes.

5.2 Managing complex systems

Products and their associated manufacturing systems are becoming more and more complex. This is a result of increasing functionality, increasing product customisation, increasingly dynamic delivery requirements, the increasing integration of different technical disciplines and organisations and the rapidly changing forms of cooperation between different companies.
Modelling can act as an enabler for managing this growing complexity. Models are a representation of a real or hypothetical scenario that only include those aspects that are relevant to the issue under consideration. The use of models constitutes an important strategy in the digital world and is of central importance in the context of Industrie 4.0.

A fundamental distinction can be drawn between two types of model:

- Planning models provide transparency with regard to the creative value-added generated by engineers and thus make it possible for complex systems to be built. An example of a planning model would be a schematic used by an engineer to explain how he or she has implemented appropriate functions to meet the requirements placed on a system. As such, the model contains the engineer's knowledge.
- Explanatory models describe existing systems in order to acquire knowledge about the system through the model. This typically involves using different analysis processes such as simulation. For example, a simulation can be used to calculate a factory's energy consumption. Explanatory models are often used to validate engineers' design choices.

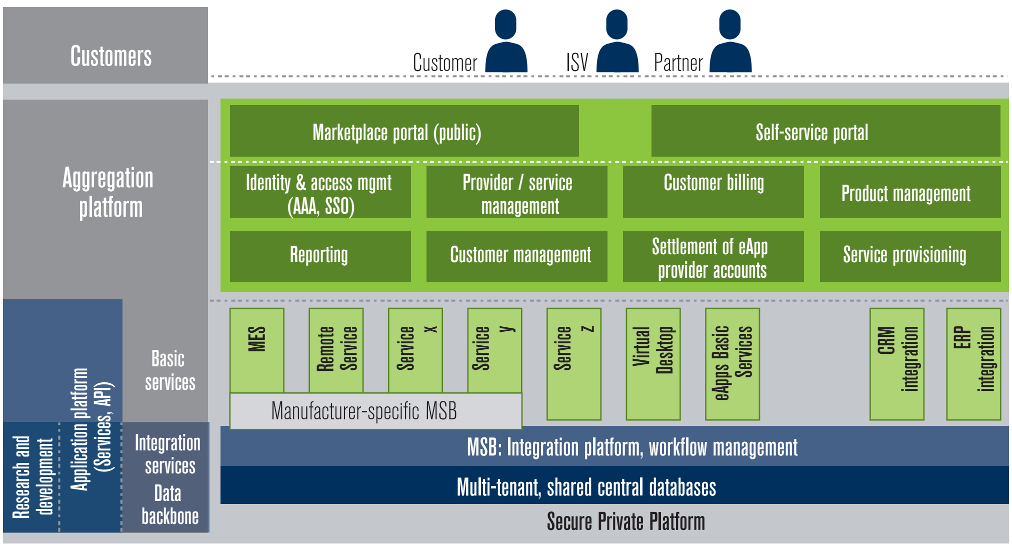
The digital world thus exerts a significant influence over real-world design via planning models, whilst the real world also influences the models used in the digital world via explanatory models.[1]
The fact that models usually contain formal descriptions means that they can be processed by computers, allowing the computer to take over routine engineering tasks such as performing calculations or other repetitive jobs. One of the **benefits** of models is therefore that they allow manual activities to be automated and enable actions to be performed in the digital world that previously had to be performed in the real world.

Models offer huge **potential** – and not only in the context of Industrie 4.0. For example, they allow the risks involved in a project to be reduced through early detection of errors or early verification of the demands placed on the system and the ability of proposed solutions to meet these demands. Or they can provide a transparent information flow that enables more efficient engineering by improving interdisciplinary cooperation and facilitating more consistent engineering data.
Explanatory models that describe interactions and behaviours in the real world are not only useful for validation purposes during the **development and design stages**. In the future, they will be primarily deployed during the **production stage** in order to check that production is running smoothly, detect wear and tear without needing to halt production or predict component failure and other disruptions.

Challenges

Particularly in SMEs, it is still not standard practice to use model-based simulations in order to configure and optimise manufacturing processes. One major challenge for Industrie 4.0 will therefore be to raise awareness of models' potential among the wider engineering community and equip engineers with **methods and tools** for using appropriate models to depict real-world systems in the virtual world (see Chapter 5.6). There are some scenarios (e.g. chemical interactions during production) where suitable models simply do not exist or where it is hard to describe them in a formal model.
The explicit development of models for Industrie 4.0 will initially involve a higher financial outlay than approaches that do not explicitly use modelling. This is because a value-added activity is being brought forward to an earlier stage in the process in order to reduce costs later on. This immediately raises the question of whether modelling is **cost-effective.** The answer is obviously very dependent on the type of business in question. Companies are likelier to accept higher initial investment levels in industries with high production volumes

Figure 11: Example reference architecture for a CPS platform



Source: Hewlett-Packard 2013

(such as the automotive industry) or industries with stringent safety standards (such as the avionics[2] sector). They are less likely to do so if they only manufacture small volumes or make individual products. The percentage of costs associated with customer-specific activities vs. customer-independent activities also plays an important role in this regard. It is key to the success of models that they should be developed cost-effectively and that they should be used productively not just during the design stage but also in the subsequent stages, including operation.

Modelling and simulation can only be carried out by qualified **experts**. It is therefore important that the relevant companies should provide these experts with the appropriate career opportunities. Currently, employees of SMEs in the mechanical engineering sector who are qualified in this area are largely regarded as "oddballs". Finally, a holistic approach should be adopted to the "introduction" of modelling for Industrie 4.0. Firstly, it will be necessary to take the **product** and **manufacturing system** into account, both in terms of equipping them with a modular design and ensuring the involvement of different disciplines (e.g. manufacturing engineering, automation engineering and IT). Secondly, the actual development, engineering and manufacturing **processes** occurring in the factory will also have to be considered on a case-by-case basis. Lastly, modelling requires efficient software **tools** that will have to be optimised and adapted to provide the necessary functionality, enable them to be integrated with existing tools and processes, and bring them into line with the roll-out strategy.

Recommended actions

The Industrie 4.0 Working Group recommends the establishment of a **Working Group** under the auspices of the Industrie 4.0 Platform to deal exclusively with the topic of **modelling as a means of managing complex systems**, particularly in the realm of manufacturing engineering. The Working Group's remit should include the following tasks:

- A representative **survey** should be carried out to establish the most pressing requirements in the field of modelling, in order to narrow down this very broad subject area to the most important aspects in terms of implementation.
- **Best practice sharing** should be carried out, particularly among SMEs, in order to promote the fundamental importance of modelling among both practitioners and decision-makers. Potential themes could include modularisation, virtual start-up or digital plant. In addition, appropriate events should be arranged to enable discussion of entry barriers and migration strategies (cf. the request for more information expressed in the survey conducted by the professional associations, Chapter 2). Moderation should also be provided for **communities** and **expert pools** that would act as a one-stop shop for answering questions about modelling from (potential) users.
- The Working Group should encourage the establishment of **common user groups** for tool users, tool manufacturers (product managers, architects) and trainers with a view to participants gaining a better mutual understanding of each other's situations. As the leading suppliers under the Industrie 4.0 initiative, the focus should be on the "machinery and plant manufacturing" target user group, in order to provide tool manufacturers with a platform for optimally addressing their requirements (e.g. in relation to integration, end-to-end capability, shortcomings and potential). It would be desirable to invite existing user groups for specific engineering tools to provide their input on the relevant topics.
- In addition, the Working Group should work on the development of the appropriate **guidelines** and **recommended actions**.

In addition to the activities of the Platform, targeted efforts should be made in terms of **training and continuing professional development** provision with regard to modelling and systems engineering. This includes both appropriate training provision for young engineers and appropriate CPD measures for experienced engineers. Training content should be specifically geared towards the requirements of manufacturing companies (see Chapters 5.5 and 5.6).
The Working Group also recommends the establishment of the appropriate **flagship projects** to deploy and test existing modelling methods and tools in order to demonstrate the value of modelling in different situations (engineering vs. operation, mass production vs. small volumes or individual products, manufacturing industry vs. process industry, in-house vs. inter-company, production vs. logistics, etc).

5.3 Delivering a comprehensive broadband infrastructure for industry

If CPS are rolled out on a widespread basis, it will in general terms be necessary to build an infrastructure that enables significantly higher-volume and higher-quality data exchange than provided by current communication networks. A core requirement for Industrie 4.0 is therefore the enhancement of existing communication networks to provide guaranteed latency times, reliability, quality of service and universally available bandwidth. In keeping with the recommendation of the National IT Summit presented in the 2011 Digital Infrastructure Yearbook, broadband Internet infrastructure needs to be expanded on a massive scale, both in Germany and between Germany and its manufacturing partner countries.[3]

"High operational reliability and data link availability are crucial for mechanical engineering and automation engineering applications. Guaranteed latency times and stable connections are key, since they have a direct impact on application performance. […] Network operators should do more to meet the wishes of businesses.

- *Binding and reliable SLAs (Service Level Agreements)*
- *Availability and performance of traffic capacity*
- *Support for data link debugging/tracing, especially provision of the relevant technical aids*
- *Provision of widely available/guaranteed traffic capacity (fixed/guaranteed broadband)*
- *SMS delivery status notification across all mobile network operators*
- *Standardised Application Programming Interfaces (APIs) for provisioning covering all providers (SIM card activation/deactivation)*
- *Tariff management*
- *Cost control of mobile service contracts*
- *Quality of service (fixed bandwidth)*
- *Affordable global roaming*
- *Widely available embedded SIM cards*
- *Satellite-based solutions for areas with no reception [N.B. in sparsely populated areas].*"

This basic infrastructure is required not just for Industrie 4.0 but for all CPS applications, including those in the areas of energy and healthcare (see Chapter 2.1).

Challenges

The overall requirements for an effective broadband infrastructure that is accessible to a large number of users are simplicity, scalability, security, availability and affordability.

Recommended actions

The Industrie 4.0 Working Group strongly recommends implementation of the recommendations for expanding Germany's broadband Internet infrastructure proposed by Working Group 2 "Digital Infrastructure" at the 2011 National IT Summit. It will be necessary to carry out studies of concrete applications in order to establish the exact bandwidths and real-time capabilities required for Industrie 4.0.

In accordance with the recommendations of Working Group 2, the Industrie 4.0 Working Group also recommends expansion of Germany's broadband Internet infrastructure.

5.4 Safety and security as critical factors for the success of Industrie 4.0

Safety and security are two key aspects with regard to manufacturing facilities and the products they make (see info panel). On the one hand, they should not pose a danger either to people or to the environment (safety), whilst on the other both production facilities and products – and in particular the data and know-how they contain – need to be protected against misuse and unauthorised access (security).
In contrast to security, safety issues have been an important consideration in the design of manufacturing facilities and the products they make for many years. Safety is regulated by a whole host of regulations and standards governing the construction and operation of such systems.[4]
Since information technology first came into contact with mechanics and electronics towards the end of the 1960s (Industrie 3.0[5]) there has been a dramatic increase in safety and security requirements in the manufacturing environment. In addition to the fact that it became far more complex to provide hard evidence of operational safety, it gradually became apparent that security was also a problem. Many of the safety and security issues that arose in Industrie 3.0 (the "beta version" of Industrie 4.0) have yet to be fully resolved. Security measures in particular are often slow to be implemented and frequently only provide partial fixes. With the advent of Industrie 4.0, a number of additional safety and security requirements are set to arise. Industrie 4.0's CPS-based manufacturing systems involve highly networked system structures incorporating large numbers of human beings, IT systems, automation components and machines. High-volume and often time-critical data and information exchange occurs between the technological system components, many of which act autonomously. At the same time, a far greater number of actors is involved across the value chain (see Chapters 2 and 3). However, safety and security are always properties of the entire system. Thus, in addition to operational safety issues, the extensive networks and at least hypothetical potential for third-party access mean that a whole new range of security issues arise in the context of Industrie 4.0. It will only be possible to implement Industrie 4.0 and get people to accept it if the following points are put into practice:

1. **Security by Design as a key design principle.** In the past, security against external attacks was usually provided by physical measures such as access restrictions or other centralised security measures. In CPS-based manufacturing systems, it is not enough simply to add security features on to the system at some later point in time. All aspects relating to safety, and in particular security, need to be designed into the system from the outset.
2. **IT security strategies, architectures and standards need to be developed and implemented** in order to confer a high degree of confidentiality, integ-

rity and availability on the interactions between these highly networked, open and heterogeneous components. They also need to provide an appropriate, reliable and affordable solution for protecting the digital process know-how, intellectual property rights and data in general of each individual manufacturer and operator, both vis-à-vis the outside world and with regard to components belonging to different operators and/or manufacturers vis-à-vis each other (see also Chapter 5.7).

In Industrie 4.0, it is therefore always necessary to adopt a global approach to safety and security. It is essential to consider the impact of security measures (cryptographic processes or authentication procedures) on safety (time-critical functions, resource availability) and vice versa ("does a particular critical safety function of a subsystem increase the risk of cyber-attacks?").

Furthermore, in view of the current situation, a **dual strategy** is also required for Industrie 4.0 with regard to safety and security. Firstly, existing factories will have to be upgraded with the safety and security measures needed to meet the new requirements. The typically long service lives of machinery and short innovation cycles, together with heterogeneous and in some cases very old infrastructures that are difficult to network mean that this will not be an easy task. Secondly, solutions for new factories and machinery will have to be developed. The transition from the third to the fourth industrial revolution should be as seamless as possible and should be implemented in a way that can be clearly

"Safety" refers to the fact that technological systems (machines, production facilities, products, etc) should not pose a danger either to people or to the environment, whilst "security" refers to the fact that the system itself needs to be protected against misuse and unauthorised access (access protection, security against attacks, data and information security). Various aspects of safety and security are relevant to Industrie 4.0, making it essential to draw a clear distinction between the two terms:

Security/IT security/cyber-security: The protection of data and services in (digital) systems against misuse, e.g. unauthorised access, modification or destruction. The goals of security measures are to increase confidentiality (the restriction of access to data and services to specific machines/human users), integrity (accuracy/completeness of data and correct operation of services) and availability (a means of measuring a system's ability to perform a function in a particular time). Depending on the technological system in question and the data and services that it incorporates, security provides the basis for **information privacy**, i.e. the protection of individuals against infringements of their personal data rights. It also enables know-how protection, i.e. protection of intellectual property rights.

Safety: The absence of unacceptable risks and threats to people and the environment resulting from operation of the system. "Safety" requires both operational safety and a high degree of reliability. Depending on the technological system in question, safety may also involve additional aspects such as prevention of mechanical or electrical hazards, radiation protection, prevention of hazards relating to steam or high pressure, etc. Operational safety refers to the aspects of safety that are dependent on the correct operation of the system or that are provided by the system itself. The elements required to deliver operational safety include low fault rates, high fault tolerance (i.e. the ability to keep operating correctly even when faults occur) and robustness (the ability to guarantee basic functionality in the event of a fault). Reliability refers to the probability of a (technological) system operating correctly for a given period of time in a given environment.

understood by all the relevant stakeholders. One key aspect for both pillars of the strategy is for all the actors throughout the entire value chain to reach a consensus on safety and security issues and the relevant architecture before implementation begins.

Challenges

There are a variety of different challenges facing safety and security in the context of Industrie 4.0. Quite apart from the technical challenges, successful safety and security solutions will also have to address commercial, psychological and educational issues. For example, industry currently lacks fully standardised operating platforms for implementing adequate safety and security solutions that have been tailored to the specific requirements of industry in terms of their implementation and cost so that they do not merely become regarded as cost drivers. There is often little that can be done to expand or upgrade existing infrastructure, especially since many safety and security solutions were originally developed for other industries or applications. Moreover, security awareness often plays a key role, particularly with regard to IT security issues. There are currently too many discrepancies regarding the level of security awareness in different industries. In view of the fact that Industrie 4.0 will involve increased networking and cooperation between several different partners in a value chain, it will be necessary for partners to have a higher level of confidence in each other's competence (security & trust) and for them to provide hard evidence of their competence.

Machinery and plant manufacturers are becoming increasingly aware of the value-added potential of software, resulting in a sharp rise in the number of software components found in manufacturing facilities and machinery. However, too little is often still known about the relevant IT threats. Industrial IT security has only started to be discussed in the automation industry since the public debate surrounding malware such as Stuxnet, Duqu or Flame. Moreover, software is also playing an increasingly important role in delivering and maintaining security and safety, but this is something that has not yet been properly taken on board by manufacturing processes – and where solutions are available they have yet to be implemented.

In general terms, Industrie 4.0 will require a much more proactive approach to safety and security than has hitherto been the case (especially with regard to security by design). At the moment, safety and security issues are often only raised reactively once the development process is over and specific safety or security problems have already occurred. However, this belated implementation of safety and security solutions is both costly and also often fails to deliver a permanent solution to the relevant problem. Consequently, safety and security cannot simply be broken down into functional components but should instead be approached as a process. In order to achieve fast response times, it is also important to provide support through monitoring and comprehensive cross-sectoral information exchanges. At the moment, there is insufficient monitoring of risk assessment indicators, particularly with regard to industrial IT security, and little if any information is exchanged about safety and security incidents. Action in these areas would help to stop the spread of viruses or indiscriminate cyber-attacks.

Recommended actions

As part of its study of cyber-security issues, the Federal Office for Information Security (BSI) drew up a list[6] of the top 10 most critical threats currently facing Industrial Control Systems (ICS). The Industrie 4.0 Working Group has worked together with a number of experts to produce a complementary list of **eight priority areas for action** in the field of safety and security:

1. Integrated safety and security strategies, architectures and standards

Industrie 4.0 will require modified safety and security strategies, together with systematic application of the relevant principles and methods throughout the entire system life cycle. A common "knowledge pool" should be developed as a basis for this approach. This would enable the strategies and processes currently used in the process automation and mechanical and electrical engineering industries to be enhanced by adapting the safety and security strategies and processes employed by the IT, automotive and aerospace industries to the specific requirements of Industrie 4.0.

- Research is needed to develop safety and security strategies for hypothetically open, collaborative subsystems belonging to different manufacturers and operators. These strategies should be based on threat scenarios that could initially be developed for individual sectors such as the mechanical engineering or automotive supply industries, but which would ultimately have to be applicable to all industries.
- It is important to ensure that research and development of the relevant strategies and systems is closely coordinated with other safety and security research projects on topics such as secure proof of identity, cyber-security or the protection of critical infrastructure and that knowledge is exchanged with other industries such as the automotive and aerospace industries.
- Building on these strategies, safety and security architectures for manufacturing systems should be defined as reference architectures for the Industrie 4.0 initiative. As far as possible, these should be backwards compatible with existing Industrie 3.0 systems.

In addition to ensuring the standardisation of approaches and procedures that is key to the success of Industrie 4.0, these reference architectures would also enable test procedures to be defined and testing facilities to be established that could be used to test the overall safety and security of systems at every level, from the individual machine to networks of machines and the application stage. The reference architectures could also serve as a basis for issuing security classifications and certificates to new and especially to existing subsystems. This approach would thus form part of the migration strategy.

2. Unique and secure IDs for products, processes and machines

Secure information exchange throughout the entire manufacturing process is key to the acceptance and success of Industrie 4.0. This applies to machines, their components, the data being exchanged, the affected processes and the organisational units involved. To enable this exchange, it is necessary for the individual machines, processes, products, components and materials to possess unique electronic IDs. Furthermore, it would be desirable to issue components with a kind of "security passport" containing details of the risks that were already taken into account and counteracted during development and the risks that need to be considered by the integrator, installer, operator or user. The passports would also contain the security classification referred to above.

As part of a secure ID, these passports could form the basis of a system for rating the overall security of a CPS in the manufacturing environment, both during its development and during production itself. The security rating would take into account the value of the product, the potential threats and the modified or appropriate countermeasures. The strategic initiative on "Secure Identities" should thus be expanded to include "products", "machines" and "processes" and should incorporate virtual products as well as physical ones.

3. A migration strategy from Industrie 3.0 to Industrie 4.0

The goal of a migration strategy would be to gradually improve the security of current Industrie 3.0 facilities (which are likely to remain in use for some considerable time) and prepare them for conversion to Industrie 4.0. However, the heterogeneity, long service lives and individual nature of existing manufacturing facilities all hamper the development of common standards for IT security solutions. Consequently, in addition to the abovementioned assessment of the current status of existing facilities, a migration strategy will also require the development of a standardised process model that enables individual security solutions to be implemented rapidly, pragmatically and cost-effectively. This process could be arrived at by adapting existing (generic) IT security processes, based on the definition of individual security goals, a situation analysis in order to identify weaknesses and threats and the subsequent establishment of a list of measures which would then be implemented.

4. User-friendly safety and security solutions

People tend to avoid using processes and applications that are not user-friendly. This can have fatal consequences for safety and security solutions, especially in a highly networked environment. It is therefore necessary to develop safety and security solutions that are geared towards users' needs, possess user-friendly interfaces and therefore guarantee execution of the application in question. These factors should be taken into account from the initial design phases through engineering and operation right up to and including maintenance.

5. Safety and security in a business management context

Inevitably, safety and security are always going to be cost factors. When machinery breaks down, there can be both a direct impact (e.g. lower turnover) and an indirect impact (e.g. compensation claims from customers, suppliers and partners or damage to the company's image). However, until now few manufacturers have taken out insurance against damage caused by IT issues. It is therefore necessary to develop methods that will enable clearer calculation of the risks associated with Industrie 4.0 and the cost-effectiveness of the relevant security solutions as opposed to the alternative of shutting down manufacturing facilities in the event of a real or suspected IT threat.

6. Secure protection against product piracy

Successful products are inevitably going to be targeted by product piracy. In a global market, intellectual property protection is therefore key to the survival of high-wage economies.[7] The problems associated with this phenomenon are not confined to its impact on sales but also include damage to corporate image and loss of know-how. In the most extreme cases, erstwhile pirates can even become competitors. Moreover, the problem is no longer restricted to the often rather complex physical replication of products – the targeted theft of corporate and product know-how is now also becoming increasingly common, especially in the form of software or configurations that are currently still easy to copy.

Protection against product piracy assumes even greater importance in Industrie 4.0 in view of the much higher degree of cooperation between the different partners in the value network. It is therefore necessary to work at a technical level and in particular at the corporate and competition law levels to find solutions that guarantee trust and transparency within the platform whilst at the same time protecting critical business know-how.

7. Training and (in-house) CPD

A knowledge of IT security issues is essential for all the members of an organisation. It is crucial to raise awareness among all the people involved in production, from skilled machine operators to security software developers and planning engineers working in the field of plant engineering. When security solutions are implemented in a business, it is not enough simply to install a technical product, even if it is user-friendly (see point 4) – employees also need to be adequately trained with regard to the relevant security requirements. Appropriate awareness-raising campaigns targeted at the manufacturing environment could help to overcome the current shortcomings in this area, whilst the introduction of compulsory classes on this topic at higher education institutions would help prepare the workforce of the future (see also Chapter 5.6).

8. "Community building" for data protection in Industrie 4.0

Industrie 4.0 will require tougher data protection arrangements, for example because it will be technically possible to record and analyse information about employees' health via the machines in smart factories or through smart assistance systems. The use of personal information is an especially sensitive issue in Germany, where there is much focus on the right to informational self-determination. Consequently, it is recommended that the topic of data protection should be addressed in close cooperation with the strategic initiative on "Secure Identities", the Federal Office for Information Security (BSI), the Federal and regional Data Protection Commissioners and the trade unions and company works councils (see Chapter 5.7).

The Industrie 4.0 Platform will need to engage in an in-depth discussion in order to establish priorities with a view to drawing up a roadmap or producing a list of requirements. When envisaging the optimal solution for Industrie 4.0, it will be important to consider not just how to deliver secure communication between machines and components but also the inherent security of individual machines. It is recommended that the focus should be on pragmatic solutions that can be promptly implemented in existing facilities without having to wait for the longer-term "ideal" solutions to be developed (see Chapter 2.1).

Germany is a world leader in both complex IT security solutions and in the field of safety, whilst Germany's safety and security experts enjoy an excellent reputation right across the globe. However, conventional IT security products are predominantly produced in other countries such as the US and Israel. In parallel to the development of CPS and CPS products, Germany has an opportunity to build its own security industry for Industrie 4.0, drawing on the competitive advantage provided by its specific know-how in manufacturing and automation processes, mechatronic engineering and embedded systems. It will be important to act swiftly to ensure that this advantage is used to its full potential in Industrie 4.0.

» Industrie 4.0 will require the development of technological and organisational solutions that are adapted to the needs of small and medium-sized enterprises. It will be necessary to take advantage of the specialist know-how within businesses. Worker-friendly work organisation and workplace-based training will be key to its implementation.«

Dr. Georg Schütte
Federal Ministry of Education and Research
State Secretary

5.5 Work organisation and work design in the digital industrial age

What impact will Industrie 4.0 have in the workplace? What responsibilities will have to be met by businesses and society in a decentralised high-tech economy where CPS are commonplace? How should the world of work respond to these changes? In a future characterised by increasing automation and real-time oriented control systems, how can we ensure that people's jobs are good, safe and fair? The answers to these questions will determine whether or not it is possible to mobilise existing reserves of innovation and productivity and secure a competitive advantage through the widespread deployment of automatically controlled, knowledge-based, sensor-equipped manufacturing systems.

Innovation efforts cannot be allowed to focus exclusively on overcoming the technological challenges. The remit of innovation needs to be consistently widened to include smart organisation of work and employees' skills, since employees will play a key part in implementing and assimilating technological innovations. It is likely that their role will change significantly as a result of the increase in open, virtual work platforms and extensive human-machine and human-system interactions. Work content, work processes and the working environment will be dramatically transformed in a way that will have repercussions for flexibility, working time regulation, healthcare, demographic change and people's private lives. As a result, in order to achieve successful integration of tomorrow's technologies they will need to be smartly embedded into an innovative social organisation (within the workplace).

Challenges

It is very likely that the nature of work in Industrie 4.0 will place significantly higher demands on all members of the workforce in terms of managing complexity, abstraction and problem-solving. Employees will also be expected to be able to act much more on their own initiative and to possess excellent communication skills and the ability to organise their own work. In short, greater demands will be placed on employees' subjective skills and potential. This will provide opportunities in terms of qualitative enrichment of their work, a more interesting working environment, greater autonomy and more opportunities for self-development.

Nevertheless, the demands of the new, virtual workplace also present a threat to the maintenance and safeguarding of human capital. As the degree of technological integration increases, there is a danger of employees being required to be more flexible and perform more demanding tasks, as well as a growing tension between the virtual world and the world of workers' own experience. This could result in workers experiencing a loss of control and a sense of alienation from their work as a result of the progressive dematerialisation and virtualisation of business and work processes. It is also possible that "old" and "new" threats could combine to take on a new dimension, resulting in significant creativity and productivity losses and a tendency for employees to overwork themselves.

Finally, it is important to consider the impact that the increasing presence of IT in manufacturing industry will have on headcount. It is likely that the number of simple manual tasks will continue to decline. This could pose a threat to at least some employee groups, notably semi-skilled workers. Such a scenario would be unacceptable both for the employees themselves and from the wider public's point of view in terms of the social inclusion dimension. Moreover, it would seriously hamper the successful implementation of the Industrie 4.0 initiative.

A consistent approach to technology and work organisation

Smart factories provide an opportunity to create a new workplace culture geared towards the interests of the workforce. However, this potential will not simply be realised of its own accord. It will be crucial to employ work organisation and design models that combine a high degree of individual responsibility and autonomy with decentralised leadership and management approaches that allow employees greater freedom to make their own decisions, be more involved and regulate their own workload, whilst at the same time also enabling flexible working arrangements.

It is possible to use the technology for very different ends. Systems can be set up to impose restrictive control over every minute detail of a person's work, or they can be configured as an open source of information that employees use as a basis for taking their own decisions. In other words, the quality of people's work will not be determined by the technology or by any technological constraints but rather by the scientists and managers who model and implement smart factories.

It is therefore necessary to adopt **a socio-technical approach** where work organisation, continuing professional development measures and technology and software architectures are developed in close conjunction with each other to provide a single, consistent solution focused on enabling smart, cooperative and self-organised interactions between employees and/or technology operating systems across the entire value chain.

"Better, not cheaper" as an opportunity and benchmark for industrial change

This socio-technical approach argues that adopting an even more extreme version of the Taylorist approach to work organisation based on frequent repetition of highly standardised and monotonous tasks is hardly the most promising way to go about implementing the Industrie 4.0 initiative in partnership with employees in a way that allows new efficiency gains to be achieved. The fact that smart factories will be configured as highly complex, dynamic and flexible systems means that they will need employees who are empowered to act as decision-makers and controllers. For this to be possible, they will need to be supported by customer-oriented job profiles requiring broad-based training, work organisation models that promote learning, and comprehensive continuing professional development that fosters autonomous work and is designed as an active instrument for promoting systematic staff development and career advancement. In Industrie 4.0, technological development goals and work organisation models should be established and configured together in accordance with the specific economic and social circumstances. It will be necessary to enable more flexible manufacturing whilst at the same time establishing clear boundaries between employees' work and private lives, enabling them to achieve a realistic work-life balance.

In this context, the innovation strategy being promoted by the trade unions under the banner of "better, not cheaper" could point the way towards robust standards and pathways for creating good and fair jobs and a secure future for manufacturing sites and their employees. The strategy incorporates a labour-oriented organisational design with enhanced participation rights, co-determination and training opportunities. Nonetheless, it is still capable of meeting the demands of global competitiveness and the need for greater flexibility. The "better, not cheaper"[8] strategy targets technology leadership as the basis for securing the future of German industry. Consequently, good jobs, technological innovation and worker co-determination are not mutually exclusive in the context of the Industrie 4.0 initiative. Rather, they form part of a forward-looking approach to the search for technologically efficient solutions that are also socially sustainable.

Recommended actions

- The Industrie 4.0 Platform should continue to study the issue of "People and Work in Industrie 4.0" through an **interdisciplinary expert working group**. The working group's remit should comprise three main goals:

  1. To ascertain and document the impact on work and employment (opportunities and risks) together with the actions required to achieve employee-oriented labour and training policies
  2. To provide guidelines and practical aids for developing and implementing the socio-technical approach, together with the relevant reference projects
  3. To promote innovative approaches to participative work organisation and lifelong learning that embrace the entire workforce, irrespective of age, gender or qualifications

- The Platform should **set up a regular dialogue between the social partners** to enable transparent identification and discussion of the key advances, problems and potential solutions associated with the implementation of Industrie 4.0.

- The Platform should arrange effective knowledge transfer between stakeholders inside and outside of companies at both national and international levels. In addition to innovative knowledge management, this will also require the establishment of broad-based social networks.

5.6 Training and continuing professional development for Industrie 4.0

As described above, the implementation of Industrie 4.0 should result in a labour-oriented socio-technical factory and labour system. This will in turn pose new challenges for vocational and academic training and continuing professional development (CPD). These challenges include the need to expand provision for the developers of manufacturing engineering components and their users.

It is likely that Industrie 4.0 will significantly transform job and skills profiles as a result of two trends. Firstly, traditional manufacturing processes characterised by a very clear division of labour will now be embedded in a new organisational and operational structure where they will be supplemented by decision-taking, coordination, control and support service functions. Secondly, it will be necessary to organise and coordinate the interactions between virtual and real machines, plant control systems and production management systems.

Effectively, what this means is that the convergence of ICT, manufacturing and automation technology and software will result in many tasks now being performed as part of a much broader technological, organisational and social context.

Industrie 4.0 will also require fundamental changes to the way IT experts are trained. The ability to identify application requirements in different industries and recruit development partners from around the world will increasingly take precedence over purely technological expertise. The extremely wide range of potential applications means that there is a limit to what can be achieved through standardised training programmes. It will become more and more important to engage in a dialogue with manufacturing industry in order to ensure that the requirements of the digital economy are reflected in training provision. As such, training partnerships between businesses and higher education institutions will be even more important in the future than they are today. Short basic training programmes will need to be followed by work placements and advanced study courses. It will be important to open up access to science and engineering studies and place greater emphasis on transferable skills such as business or project management. It is businesses and their customers who should drive the changes made to the academic training of IT experts.

In keeping with the principles underpinning Industrie 4.0, this will also involve close convergence of IT and production engineering training. The relevant learning content for Industrie 4.0 will thus need to be identified and the appropriate didactic and methodological approaches will need to be developed. It is possible that in particular some of the creative areas of businesses such as interdisciplinary product and process development could require completely new qualifications. These would form part of a dual strategy that would enable companies to respond to the challenges of a shrinking labour market and high market volatility.

In this context, it will be key to develop professional adult education provision (teaching methods, career profile). **Skills assessments**[9] should be used to improve mobility between vocational and academic education and between the different training and CPD programmes and systems, as well as to improve recognition of skills that are still relevant in the workplace despite not being connected to an employee's specialist area. There is a growing need for people to have a grasp of the overall context and to understand the interactions between all the actors involved in the manufacturing process. Consequently, in addition to increased demand for metacognitive skills, social skills are also gaining in importance owing to the growing significance of real-life and computer-based interactions resulting from greater integration of formerly demarcated departments and disciplines. In technical terms, much greater emphasis will be placed on interdisciplinary skills, an area where much work still remains to be done.

In order to ensure that individuals' training potential can be recognised and described transparently, it will be necessary to develop standards for the recognition of non-formal and informal education. The goal is to teach people the principles of a new, holistic organisational model and ensure that systems are described transparently so that employees are confident in what they are doing.

The Academy Cube

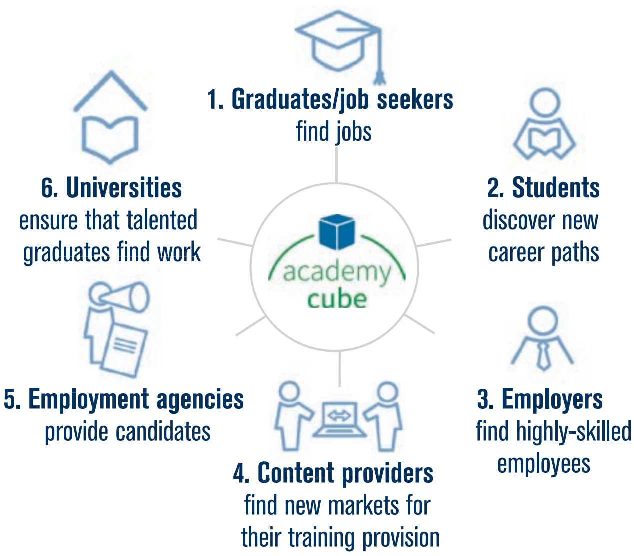
The **Academy Cube** is an initiative that has been launched by German and international industrial enterprises together with public institutions in order to address the need for new training formats and content arising from Industrie 4.0. Current provision specifically targets skilled workers from southern Europe, where unemployment* rates are particularly high. The Academy Cube provides online information to interested parties about how they might be able to use their skills and knowledge both in their home country and abroad.

The **Academy Cube** offers unemployed graduates in ICT and engineering the opportunity to obtain targeted qualifications and helps put them directly in touch with industrial enterprises. This is achieved via a cloud-based platform where companies and institutions provide e-learning courses and post specific job vacancies. The platform helps job seekers to obtain the training they need to apply for specific vacancies, whilst also issuing them with the corresponding certificates. These certificates, that are based on standard curricula, ensure that potential employers can be confident about the standard of the training and provide transparency with regard to its content. The best candidates are automatically directed to the top job vacancies of the participating companies.

The **Academy Cube** concept was developed during the BMBF- and SAP AG-chaired Working Group 6 on Education and Research for the Digital Society at the National IT Summit and was officially launched at CeBIT 2013. Since March 2013, the programme has been offering six full curricula and twelve specific courses in the area of Industrie 4.0. Learning content includes fields such as automation, big data analysis, manufacturing and logistics processes and security and data protection.

More information is available at: **www.academy-cube.com**

Figure 12:
Networking different actors though the Academy Cube



Source: Academy Cube 2013

* In 2012, unemployment in Spain stood at 27 percent, whilst youth unemployment in Spain and Greece was as high as 52 percent (Source: Eurostat 2012). The European Commission estimates that by 2015 there will already be a shortage of 700,000 ICT professionals in Europe (Source: European Commission News, 20.3.2012); BITKOM calculates that there is an annual shortfall of 9,000 IT graduates in Germany (Source: BITKOM 2012). 10,100 additional ICT experts are needed in Italy, 18,300 in Poland, 41,800 in Spain and 87,800 in Germany (Source: Eurostat 2012).

Whilst all the different levels of the training system are affected, special priority should be attached to the expansion of CPD. In particular, **CPD in the workplace** should address the importance of health, physical activity and lifestyle in ensuring a lengthy working life.

By organising work in a way that fosters learning and implementing appropriate training strategies, it should be possible to achieve a human-centric approach to manufacturing that takes account of differences in employees' education, experience and skills sets in a way that strengthens the innovative capacity of both individuals and businesses. The organisation of work in a way that fosters learning is also a key requirement for lifelong learning. In view of the rapid technological changes expected as a result of the introduction of CPS-based systems, it should therefore also be one of the goals of the smart factory. The comparative effectiveness of in-house versus out-of-house learning and general versus vocational education should be the subject of further research.

In addition, Industrie 4.0 jobs will be designed to use technologies such as CPS in order to enhance communication between employees and integrate job support, learning tasks and physical training in the workplace into the standard working day at suitable intervals. This will require employees' workload to be monitored on an ongoing basis.

Job design should also take into account the different roles performed by employees (from unskilled and skilled workers or employees with advanced vocational and technical qualifications to staff members with academic qualifications such as bachelor's and master's degrees or qualified engineers) as well as differences in their circumstances such as age, education, experience or cultural background.

Recommended actions

The Industrie 4.0 Working Group recommends the following measures with regard to qualifications, training and CPD in the context of Industrie 4.0:

1. **Promotion of model projects**
   Projects should incorporate actions that can be used to develop training and CPD strategies. These should include strategies to promote mobility between vocational and academic training and between different training and CPD courses and systems as well as to recognise additional skills that employees possess outside their specific area of expertise.
2. **Establishment and promotion of "best practice networks"**
   In order to guarantee knowledge transfer and sustainability, training and CPD "best practice networks" should be established by competitive tender. These networks would be charged with developing and documenting case studies, networking the various actors and supporting knowledge transfer.
3. **Investigation of new approaches to knowledge and skills acquisition in the workplace, development of digital learning techniques**
   Digital media and innovative learning technologies (e-learning) will play a prominent role in knowledge transfer and skills development. In view of technological and demographic change and the fact that different learners have different requirements, it will be necessary to develop new teaching methods and learning assistance systems.
4. **Promotion of cross-cutting approaches to work organisation**
   All Industrie 4.0 qualification, training and CPD measures will need to be accompanied by comprehensive research in the shape of research and implementation partnerships.

It will be of fundamental importance to investigate issues relating to work organisation, process design, management and cooperation, together with their impact on the evolution of work and training in Industrie 4.0. This should also include the issue of how older workers can retain their employability against a backdrop of increased life expectancy. In order to organise work in a way that fosters learning, it will be necessary to develop the appropriate training strategies, analysis methods and management models. Overall, this will present a number of significant challenges for training and CPD, including the need for comprehensive continuing professional development provision and changes to at least some parts of the training system.

5. **Promotion of Industrie 4.0-specific learning content and interdisciplinary cooperation**
   It will be necessary to promote interdisciplinary cooperation between all disciplines (e.g. manufacturing engineering, automation engineering and IT) to deliver a systems engineering approach. This will require the different disciplines to acquire a mutual understanding of each other's positions and approaches and to adopt an integrated view of strategy, business processes and systems. Interdisciplinary research will also be necessary at the interface between technology and the law. Legal experts should be involved from the early stages of the R&D process. By the same token, engineers will increasingly need to acquire a basic understanding of the legal issues so that they can engage in a full dialogue with their legal counterparts.
6. **IT-based modelling of technological systems**
   This includes modelling of the interaction between the real and digital worlds, including the appropriate formal descriptions, as well as methodological aspects such as modelled mechatronic engineering or contemplating the development of adaptations to existing systems (delta engineering) as opposed to developing completely new systems from scratch.

5.7 Regulatory framework

Just like any other fundamental technological innovation, the new manufacturing processes associated with Industrie 4.0 will find themselves confronted with the existing regulatory framework, a situation that raises two interconnected challenges. On the one hand, uncertainty regarding the legality of a new technology or the associated liability and data protection issues could inhibit its acceptance and slow down the innovation process. Conversely, the de facto power of new technologies and business models can be so great that it becomes almost impossible to enforce existing legislation. Consequently, short technological innovation cycles and the disruptive nature of new technologies can result in the danger of a chronic "enforcement deficit" whereby current regulation fails to keep pace with technological change.

While Industrie 4.0 does not, on the whole, tread completely uncharted regulatory territory, it does significantly increase the complexity of the relevant regulatory issues. Two things are required to reconcile regulation and technology: the formulation of criteria to ensure that the new technologies comply with the law and development of the regulatory framework in a way that facilitates innovation. In the context of Industrie 4.0, it will often be possible to achieve this through common law contracts. Both factors require the regulatory analysis of new technologies to begin as early as possible during the R&D phase rather than being left until they are already in use.

Challenges

1. Protecting corporate data

As the Internet of Things becomes established in smart factories, both the volume and the level of detail of the corporate data generated will increase. Moreover, business models will no longer involve just one company, but will instead comprise highly dynamic networks of companies and completely new value chains, as demonstrated by the RAN Project[10], for example. Data will be generated and transmitted autonomously by smart machines and these data will inevitably cross company boundaries. A number of specific dangers are associated with this new context – for example, data that were initially generated and exchanged in order to coordinate manufacturing and logistics activities between different companies could, if read in conjunction with other data, suddenly provide third parties with highly sensitive information about one of the partner companies that might, for example, give them an insight into its business strategies. New instruments will be required if companies wish to pursue the conventional strategy of keeping such knowledge secret in order to protect their competitive advantage. New, regulated business models will also be necessary – the raw data that are generated may contain information that is valuable to third parties and companies may therefore wish to make a charge for sharing them. Innovative business models like this will also require legal safeguards (predominantly in the shape of contracts) in order to ensure that the value-added created is shared out fairly, e.g. through the use of dynamic pricing models.

Current regulation of the protection of corporate data only addresses some aspects of these dangers and generally requires the data to be classified as business or trade secrets. Furthermore, it usually only applies to cases of illegal disclosure. As a rule, confidential information that has been acquired legally, e.g. with the permission of its owner, may subsequently be used for other purposes. However, self-regulation such as confidentiality agreements should make it possible to close these legal loopholes. Contract law offers a means of achieving highly specific regulation of a variety of different scenarios. This will require the sensitivity of the data and the degree of protection needed to be determined on a case-by-case basis – under certain circumstances, individual data protection law principles could provide a model in this regard.

However, contracts do have their limitations when it comes to managing large volumes of voluntary legal arrangements, since a disproportionately large amount of work is involved in calculating the risks and negotiating separate contracts for each individual case. It is therefore necessary to develop new contractual models that allow businesses to retain sovereignty over “their” data whilst still facilitating entrepreneurial flexibility.

2. Liability

When sensitive data are exchanged between different companies, there is a risk that they may be used and/or disclosed illicitly, or that they may be hacked by third parties if, for example, the recipient fails to implement adequate IT security measures. One solution to this problem is provided by a type of contractual clause already in widespread use that sets out the requisite technical and organisational arrangements and any additional measures (e.g. the duty to provide notification of any security problems or breaches) and stipulates penalties in the event of non-compliance. However, in Industrie 4.0 manufacturing facilities are responsible for a wider range of matters than in the past. They may now be subject to a liability action not only if they fail to meet their primary responsibilities (in terms of the product’s durability, correct operation and appearance), but also for failings in their role as part of a network of smart objects.

In these scenarios, the issue of liability and responsibility becomes even more important – when autonomous systems are deployed in networks, a lack of structural transparency could make it almost impossible to explicitly determine who performed a particular action, resulting in uncertainty with regard to legal liability. It is true that businesses employing manufacturing systems that use autonomous data processing are legally liable for the security of their manufacturing facilities and products vis-à-vis third parties. Current tort and product liability law already provides adequate solutions in this area. However, if the other partners in a network wish to avoid being held jointly liable, or if they want at least to have recourse against the other partners, then it is essential for their responsibilities to be contractually stipulated from the outset and/or for actions to be clearly attributed to the owners of the respective systems. This also has implications for the insurability of residual risk and the way that the insurance industry calculates the relevant premiums.

Correct attribution of liability will be facilitated by the provision of precise documentary evidence concerning the different manufacturing steps and system statuses (although highly detailed protocol data relating to specific individuals could cause data protection law problems). Consequently, technology-based documentation procedures such as personal or device-based digital signatures will play a far more important role in Industrie 4.0.

3. Handling personal data

As the interaction between employees and CPS increases, so will the volume and level of detail of the personal data held for individual employees. This is especially true of assistance systems that record information about an employee's location, their vital signs or the quality of their work. This issue could pose a threat to employees' right to informational self-determination. Scenarios with an international dimension are particularly problematic in this regard. German data protection law places strict restrictions on the outsourcing of the analysis of data captured in smart factories to companies located outside the European Union (EU) or European Economic Area (EEA) (including companies belonging to the same group) or the disclosure outside Europe of corporate data containing personal information about employees. This restriction is particularly applicable if data protection standards in the country receiving the data are lower than those found in Europe. This could result in problematic constraints for globally networked value chains.

Current regulation fails to adequately address these problems. Outsourced data processing models are already encountering difficulties (e.g. in the realm of cloud computing), since local data protection standards are generally not applicable in countries outside of Europe, meaning that in practice it is impossible for client companies to comply with their data protection responsibilities.

Businesses therefore have a growing need for a legally unambiguous and practical solution for handling personal data. It may be possible, up to a point, to achieve this through in-house binding corporate rules, collective agreements and company agreements, although it would be important to ensure that these did not under any circumstances undercut existing data protection standards. In any event, these instruments would need to be adapted to take account of the specific characteristics of Industrie 4.0.

The data protection law requirements for custom product features will depend on the product and application in question. One issue that is especially relevant to Industrie 4.0, for example, is the incorporation of data processing components into the end product. Whilst these components may initially be used during the manufacturing process, they may eventually come into the possession of end customers who use them for purposes for which they were not originally intended. In order to prevent this from happening and restrict the kind of data processing that the built-in components can be used for, their capabilities should be confined to what is strictly necessary as defined by data protection law.

4. Trade restrictions

As more and more complex systems are deployed in Industrie 4.0, it becomes increasingly likely that individual components may be subject to national and international trade restrictions. Encryption technologies are both necessary and desired by customers in order to ensure the confidentiality and integrity of CPS communication. However, in many emerging markets, such as China, the use, sale, importing and exporting of encryption products are only permitted under licence. In the EU, on the other hand, shipment of encryption technologies is allowed within Europe and to certain other countries such as Japan, Canada and the US, but they are classed as dual use goods[11] and subject to export restrictions for many other destinations. Even today, companies wishing to have a global presence in tomorrow's key markets are to some extent already finding themselves forced to operate in legal grey areas if cryptographic components are built into larger manufacturing facilities. This legal uncertainty will only increase in Industrie 4.0 and could become a significant barrier to trade.

Recommended actions

The regulatory challenges described above are not trivial and it will be essential to find solutions to them if the Industrie 4.0 initiative is to succeed. For the most part, these "solutions" will not entail legislation, but will instead require a mix of instruments comprising regulatory, technical and policy elements. Moreover, it will be important to raise awareness of the problems outlined above among SMEs by engaging professional associations and government ministries to act as multipliers.

One aspect that will be especially important for SMEs is the development of practical guidelines, checklists and model contract clauses. New contract models need to guarantee protection of business and trade secrets on the one hand, whilst also ensuring that any value-added generated through the new business models is shared out fairly. It will therefore be necessary to define the roles of the various partners as precisely as possible (including new roles such as different types of information broker).

As far as liability is concerned, the support provided should focus on data security and the requirement to provide documentary evidence, particularly at critical points where items are handed over from one partner to another. As for employee data protection, best practice models containing sample company agreements should be developed in order to ensure that the requirements of Industrie 4.0 do not encroach upon employees' data protection rights. With regard to the secure and confidential handling of sensitive corporate data belonging to third parties, it would be desirable to engage in efforts to promote self-regulation through measures such as audits or certification of compliance with IT security standards. Nonetheless, it will still be necessary to legislate on certain issues. These include outsourcing of data processing activities, although it is at EU level that the need for legislation in this area currently exists.

There is also an urgent need for harmonisation in the field of trade restrictions, especially with regard to encryption products. In order to ensure that Germany can successfully sustain a position as a leading supplier for Industrie 4.0, efforts should be undertaken in the medium to long term to promote common international regulations, for example through the World Trade Organization.

In more general terms, the challenges posed by Industrie 4.0 in the areas where technology comes into contact with regulation will require interdisciplinary research. It will be important to ensure that legal experts are involved right from the earliest stages of the R&D process. By the same token, engineers will increasingly need to acquire a basic understanding of the legal issues so that they can engage in a full dialogue with their legal counterparts. A partnership along these lines between engineers and legal experts could provide Germany with a genuine competitive advantage in the Industrie 4.0 market. As such, it will be necessary for the Industrie 4.0 Platform to ensure that legal experts are involved in the various working groups from an early stage.

5.8 Resource efficiency

The nature of manufacturing industry means that it is by far the largest consumer of raw materials in industrialised nations. Together with the private sector, it is also the principal consumer of primary energy and electricity. In addition to the high costs involved, this situation entails risks to the environment and security of supply which need to be minimised by regulation. Consequently, industry is undertaking major efforts to reduce its consumption of energy and resources or find alternative sources. However, these efforts will need to be sustained over many years if they are to have any chance of succeeding. Ultimately, this will involve changes in manufacturing processes and the design of machinery and plant, since these are the only areas where material and energy consumption can really be influenced.
The starting point is the amount of resources that are used by manufacturing companies, both within the company itself and throughout the rest of the value network. It is possible to draw a distinction between three categories of resources and how they are used:

1. Raw materials, additives, operating supplies and all the different kinds of energy carriers, including conversion from one type of energy into another
2. Human resources, i.e. human labour
3. Financial resources, i.e. the necessary investment and operating costs

In terms of how these resources are used, it is possible to focus on maximising the output achieved with a given quantity of resources, or on using the lowest possible quantity of resources to achieve a given output. In the first scenario, the emphasis is on calculating **resource productivity**, whilst in the second scenario the focus is on calculating **resource efficiency.** A range of metrics are now available to perform these measurements (Life Cycle Assessments, carbon footprinting[12], etc).

Challenges

In general terms, Industrie 4.0 will need to investigate and implement ways of reducing the resources consumed during industrial manufacturing processes as a whole and by the machinery and equipment used during production. The outcomes of the joint Federal Ministry of Education and Research (*BMBF*) and German Engineering Federation (*VDMA*) "Efficiency Factory" (*Effizienzfabrik*)[13] initiative could serve as a model in this regard. When implementing efficient manufacturing processes it is important to consider not only basic functions but also the stability of the processes under dynamic conditions, such as frequent stopping and starting and prevention of faulty products (which are a waste of materials and energy).
It is therefore necessary to consider **productivity** in terms of preventing unstable processes that result in quality issues which in turn require the product to be repaired or completely remade. **Availability** also needs to be considered. Manufacturing equipment can break down (so it is important to build in redundancies to minimise the risk of failure), resources may not be readily available when needed and inventory levels may not be in line with requirements (semi-finished and finished goods).

One of the key challenges for Industrie 4.0 will be to demonstrate that the additional resources invested in the deployment of CPS and the associated infrastructure can generate sufficient opportunities to deliver resource productivity and efficiency gains based on the total amount of resources used during engineering, manufacturing, production control, intralogistics, procurement and distribution logistics.
Industrie 4.0 provides the opportunity to optimise delivery of the overarching goals of resource productivity and efficiency on a case-by-case basis.

Recommended actions

The Industrie 4.0 Working Group recommends that a **Working Group** should be established through the Industrie 4.0 Platform to deal exclusively with the topic of resource productivity and efficiency. The Working Group's remit should include the following tasks:

- Adoption and development of the outcomes of the BMBF/VDMA "Efficiency Factory" initiative.
- Demonstration of resource savings in terms of enhanced resource productivity and efficiency in the manufacturing environment based on the avoidance of substitution processes resulting from productivity or availability issues.
- Calculation and assessment of trade-offs between the additional resources required to deploy CPS and their associated infrastructure and the potential savings generated. This should also be done for the different categories of resources when it comes to taking decisions on modernising production lines or building new ones and the type of automation equipment required. These assessments should take account of the industry or sector in question and whether the value network is regional or global in scope.
- It will be necessary to take account of the various metrics and KPIs (key performance indicators) that are being used to assess resource productivity and efficiency and eco-friendliness in current projects and initiatives. The development of decision-supporting KPIs such as the Green Production Index should also be taken into account, together with the basic data required to take transparent, resource-oriented investment decisions, particularly in the area of industrial automation.

1 Models can address a very wide variety of real or hypothetical scenarios, for example technological systems such as products, manufacturing resources or entire manufacturing systems, living things, e.g. human behaviour or biological interactions, physical or chemical interactions and effects or organisations, e.g. organisational structures and business processes or flows.

2 Avionics (a term derived from the words "aviation" – from the Latin avis, or bird – and "electronics") refers to all the electrical and electronic equipment on board an aircraft.

3 The following quotation is taken from: Arbeitsgruppe 2 des Nationalen IT Gipfels (Ed.): Digitale Infrastrukturen. Jahrbuch 2011/2012, 2012, pp. 176-177.

4 Examples of these regulations include the European Machinery Directive 2006/42/EG and its German transposition in the shape of the Ninth Regulation of the Equipment and Product Safety Act, 9. ProdSV.

5 The first programmable logic controller (Modicon 084) was deployed in manufacturing in 1969, see Chapter 1.

6 BSI Cyber-Security Analyses, BSI-A-CS 004, Version 1.00, 12.4.2012.

7 According to the latest survey carried out by the German Engineering Federation (VDMA), Germany's machinery and plant manufacturing sector lost just under 8 billion euros worth of sales to piracy in 2011, a rise of 24 percent since the last survey two years ago. If the money lost in this way could be recuperated, it would be enough to pay for 37,000 jobs in the industry. Almost two thirds of the companies that participated in the survey are now affected by product piracy, rising to 93% for companies with more than 1,000 employees which are generally the companies that are most active internationally (see VDMA: Studie der Arbeitsgemeinschaft Produkt- und Know-how-Schutz, Produktpiraterie 2012, November 2012).

8 See Tanja Fondel/Jochen Schroth: Innovationsführerschaft durch Mitbestimmung? In: Martin Allespach/Astrid Ziegler (Ed.): Zukunft des Industriestandortes Deutschland 2020, Marburg, 2012, pp. 174-192.

9 The German Qualifications Framework (DQR) establishes eight skill levels based on the complexity of the task and domain and the extent to which independent decision-taking is involved. According to the industry's professional associations and trade union, "skills" are defined as "the individual ability to act independently in current and future open-ended and complex situations", in: BITKOM, Gesamtmetall, VDMA, ZVEI (Ed.): Die Anforderungen des Beschäftigungssystems. Ein Beitrag zur Gestaltung des Deutschen Qualifikationsrahmens, 2007, p. 10.

10 The RAN (RFID-Based Automotive Network) project is one of 14 projects under the auspices of the Federal Ministry of Economics and Technology's "AUTONOMICS: Autonomous, simulation-based systems for small and medium-sized enterprises" technology programme. RAN aims to deliver transparent and optimal process control in the automotive industry. The project is investigating new approaches and methods for cost-effective inter-company management of order fulfilment processes. Workstream 3 is developing a standardised IT infrastructure ("information broker") enabling auto ID data to be exchanged between different companies so that they can be used to improve business processes. More information is available at: www.autoran.de.

11 The term "dual use goods" is used, particularly in the field of export control, to describe goods that may be used for more than one purpose (e.g. machines, software or technologies). Although these goods may have been produced primarily for civilian applications, their properties (e.g. the materials they contain or their performance specifications) mean that they can also be used for military purposes.

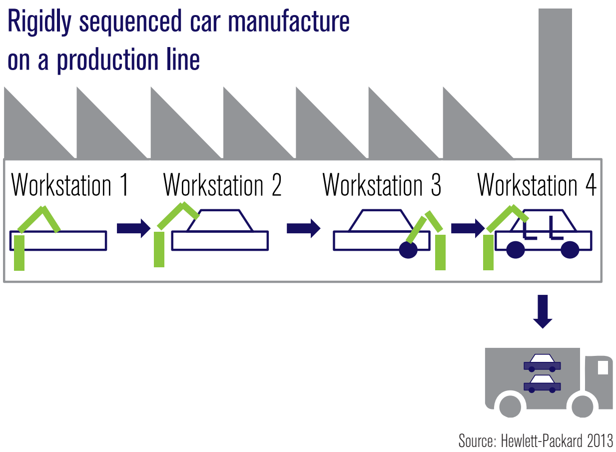
12 Life Cycle Assessments (LCAs) involve a comprehensive analysis of a product's total impact on the environment (including anything extracted from the environment for their manufacture, such as ores or crude oil, and any substances released into the environment, such as waste or CO2 emissions) throughout the course of its entire life cycle, including its manufacture, use and subsequent disposal, as well as the associated upstream and downstream processes (e.g. production of the relevant raw materials, additives and fuels; see also ISO standards 14040 and 14044). LCAs can be used during the product planning and design phases in order to ensure that the product is designed to be sustainable, as well as to help formulate product declarations during the marketing phase and for re-design purposes. A product's carbon footprint refers to its total greenhouse gas emissions throughout its entire life cycle. In other words, this indicator narrows the scope of LCAs down to a product's impact on climate change.

13 The joint BMBF (Federal Ministry of Education and Research) and VDMA (German Engineering Federation) "Efficiency Factory" innovation platform disseminates the research findings of the 31 projects grouped together under the BMBF funding priority "Resource Efficiency in Manufacturing". The platform focuses on analysing trends across the different individual projects in order to enable the development of integrated solutions for resource-efficient manufacturing that can subsequently be made available to interested companies. More information is available online at: www.effizienzfabrik.de.

EXAMPLE APPLICATION 3: Supporting custom manufacturing: how an individual customer's requirements can be met

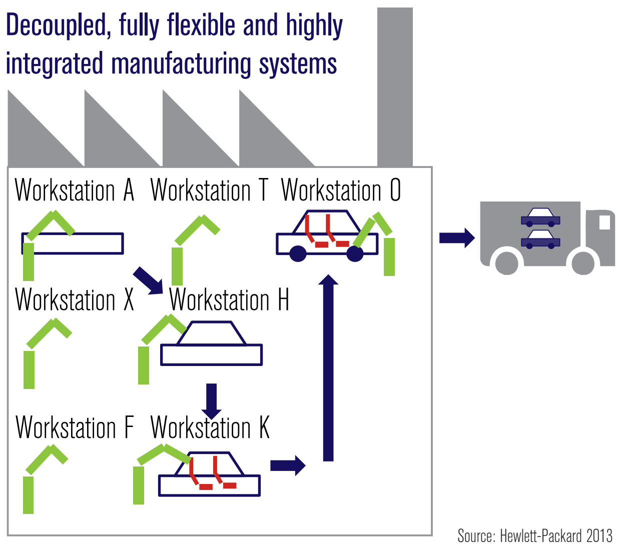
The dynamic value chains of Industrie 4.0 enable customer- and product-specific coordination of design, configuration, ordering, planning, production and logistics. This also provides the opportunity to incorporate last-minute requests for changes immediately prior to or even during production.

Today



Today's automotive industry is characterised by static production lines (with predefined sequences) which are hard to reconfigure to make new product variants. Software-supported Manufacturing Execution Systems (MES) are normally designed with narrowly defined functionality based on the production line's hardware and are therefore equally static.
The nature of employees' work is also determined by the production line's functionality and is thus usually very monotonous. Individuality is not encouraged.
As a result, it is not possible to incorporate individual customer requests to include an element from another product group made by the same company, for example to fit a Volkswagen with Porsche seats.

Tomorrow



Industrie 4.0 results in the emergence of dynamic production lines. Vehicles become smart products that move autonomously through the assembly shop from one CPS-enabled processing module to another. The dynamic reconfiguration of production lines makes it possible to mix and match the equipment with which vehicles are fitted; furthermore, individual variations (e.g. fitting a seat from another vehicle series) can be implemented at any time in response to logistical issues (such as bottlenecks) without being constrained by centrally prescribed timings. It is simple to execute this type of reconfiguration and the cars move autonomously to the relevant workstation. The Manufacturing Execution System IT solution now constitutes a central component from start to finish – from design through to assembly and operation.

POTENTIAL BENEFITS

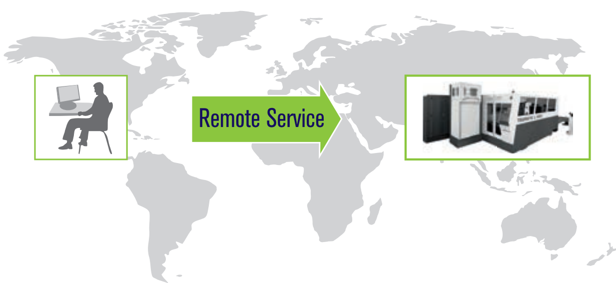
The first apps, MOS solutions and shared IT platforms as described above will start to appear relatively soon, i.e. within the next few months. However, it will be some years before we see end-to-end, CPS-enabled dynamic production lines. Nonetheless, implementations focused on specific parts of the manufacturing process can be expected to occur somewhat earlier.

EXAMPLE APPLICATION 4: Telepresence

Remote Service is an instrument that manufacturers have been using for several years in order to provide customers with fast and efficient support by remotely accessing and controlling machines. Increased networking of manufacturing systems opens up new potential to deliver additional productivity gains.

Today

Remote Service is enabled by the establishment of individual communication solutions between the machine supplier and the user. The technician generally connects to the machine directly via a modem. Since the advent of the Internet, VPN connections (Virtual Private Networks) have also gained in popularity, since they allow secure access to the customer's corporate network. The goal of this approach is to remotely diagnose and control the machine in order to reduce the duration of unscheduled stoppages and downtime.

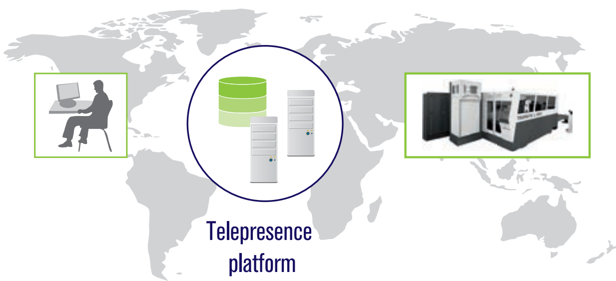


Source: Trumpf 2013

The configuration and administration of the communication links involves a significant amount of management work, since the conditions of use need to be agreed separately with each customer. Moreover, this approach can currently only be used to provide reactive services, i.e. to carry out maintenance after an incident has occurred.

Tomorrow

In Industrie 4.0, technicians will no longer manually connect to the machine they are servicing. Manufacturing systems will operate as "social machines" – in networks that are similar to social networks – and will automatically connect to cloud-based telepresence platforms in order to search for the appropriate experts to deal with the situation in question. The experts will then be able to use integrated knowledge platforms, videoconferencing tools and enhanced engineering methods to perform traditional remote maintenance services more efficiently via mobile devices. Moreover, machines will continuously enhance and expand their own capabilities as the situation requires by automatically updating or loading the relevant functions and data via standardised, secure communication links with the telepresence platforms.



Source: Trumpf 2013

By shifting complex computational tasks (e.g. simulations and projections) away from the machines to the portals it will be possible to employ huge amounts of processing power to ensure that they are performed in the shortest possible time, thus delivering additional productivity gains.

POTENTIAL BENEFITS

The first cloud-based telepresence portals that have recently become available hint at what may be possible in the future. Rapid development of these portals will open up new horizons, revolutionising manufacturing systems over the next few years.

6 How does Germany compare with the rest of the world?

6 How does Germany compare with the rest of the world?

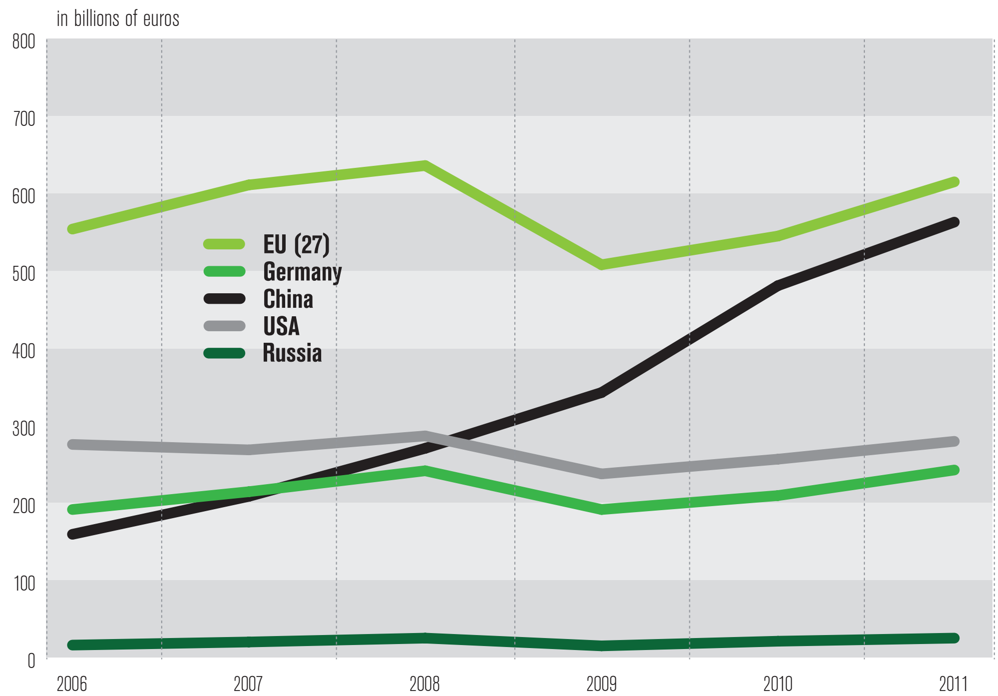
Germany is not the only country to have identified the trend towards using the Internet of Things in manufacturing (Industrial Internet[1]) and its disruptive impact on industrial processes as strategic challenges for manufacturing industry going forward. However, a variety of different terms are used around the world to describe the phenomenon of Industrie 4.0. Especially in the English-speaking world and at EU level, it is customary to refer to the Internet of Things and the trend towards digitalisation in terms of a third Industrial Revolution. This number is arrived at either by including the second Industrial Revolution (the establishment of mechanical mass production) as part of the first,[2] or not counting the third transformation of industry resulting from the automation of manufacturing processes as a genuine revolution in its own right.[3,4]

The terms “Smart Production”, “Smart Manufacturing” or “Smart Factory” are used in Europe, China and the US[5] to refer specifically to digital networking of production to create smart manufacturing systems, whereas the equally fashionable term “Advanced Manufacturing” embraces a broader spectrum of modernisation trends in the manufacturing environment.[6]
As far as the global markets for machinery and plant manufacturing, electrical engineering, automation and ICT are concerned, the examples of selected countries serve to illustrate different policy responses to these trends.

International market trends

Following a period of spectacular growth between 2004 and 2008, when output rose by approximately 38 percent, the global financial crisis triggered a dramatic slump in orders and production among Germany’s **machinery and plant manufacturers**. However, business started to pick up again as early as the middle of 2009 as companies strove to make up the ground lost during the crisis. Demand has now returned to normal, with two percent growth forecast for 2013.

Figure 13:
Mechanical engineering industry sales in selected countries*



* Mechanical engineering industry not including services such as installation, repair and maintenance; as far as possible, the sales figures include all the companies that manufacture in the respective countries

Source: VDMA, Stand November 2012

» During the course of our work together it has become apparent that Germany possesses all the necessary competencies in the fields of manufacturing technology and mechanical engineering to continue to enjoy global success in tomorrow's world of the Internet of Things and Services «

Dr. Siegfried Dais
Robert Bosch GmbH
Co-Chair of the Industrie 4.0 Working Group

According to a recent survey by the German Engineering Federation (VDMA), the majority of German mechanical engineering firms still see themselves as among the world's leaders and regard their main competitors as domestic ones, followed only distantly by competitors from the US and Italy. Global sales in the mechanical engineering sector came to around 2.1 trillion euros in 2011. A glance at the position of the mechanical engineering industry in selected countries reveals an extremely heterogeneous picture. (see also Fig. 13).

Since 2002, large-scale transfers of production to other parts of the world have resulted in a sharp increase in the US mechanical engineering sector's dependency on imports. The number of people employed in the industry fell by 25 percent between 2002 and 2010.[8] However, there have been some signs of a gradual recovery since 2010, with rises in both domestic and export demand. The press in the US has been quick to seize on terms such as "reshoring"[9] and "insourcing boom"[10] to describe what it already perceives as a fundamental sea change.

China is also devoting a huge amount of effort to catching up with other countries in terms of its mechanical engineering technology and strengthening its market position. Over the past five years, it has risen to become the world's largest machinery manufacturer, with sales of 563 billion euros in 2011. At the same time, China has also redoubled its efforts on the exports front. In 2011, the Chinese investment goods industry exported goods worth 87.7 billion euros, an increase of more than 20 percent compared to the previous year. It thus leapt forward to become the world's fourth largest exporter of machinery, with a 10.2 percent share of the market.
There has been a pronounced rise in Russia's demand for machinery and plant since 2010. **Russia**, which is the official partner country of this year's Hannover trade fair, is already the fourth largest export market

for German mechanical engineering firms, behind China, the US and France. Germany is also Russia's number one machinery supplier, with a 22.6 percent market share. The Russian government is forecasting continued growth of the Russian market over the next few years and is supporting this growth through a funding programme worth billions of euros. In the longer term, there is significant potential for German machinery and plant manufacturers to export Industrie 4.0 products to Russia.

In 2011, the global electrical engineering market was worth 3,414 billion euros. At 116 billion euros, the **German electrical engineering market** is the fifth largest in the world, after China (1,119 billion euros), the **US** (486 billion euros), Japan (284 billion euros) and South Korea (155 billion euros). In recent years, the growth of the global electrical engineering market has largely been due to newly-industrialised countries whose total market volume of 1.7 trillion euros reached the same level as that of the industrialised nations for the first time in 2011. It is expected that growth will remain significantly higher in the newly-industrialised countries than in the industrialised nations during 2012 and 2013.

The global **automation** market recently reached 350 billion euros, meaning that it now accounts for more than one tenth of the global electrical engineering market. In the past few years, **China** has risen to become the single largest regional market. Its market is currently worth 100 billion euros, giving it a 29 percent share of the global market and meaning that it has now overtaken **Europe**, where the market is worth just 93 billion euros. Trailing some way behind these two markets are the **US** (12 percent or 40 billion euros) and Japan (8 percent or 26 billion euros). At 21 billion euros (6 percent), **Germany** is the world's fourth largest market.

China's lead is even greater when it comes to automation product manufacturing. **China** accounts for 30 percent of global production, or 103 billion euros out of a total of 350 billion euros. The **US** and Japan are more or less tied for second place with roughly eleven percent each, closely followed by **Germany**, with ten percent. However, Germany is the world's largest exporter of automation products and systems (29 billion euros), followed by China (27 billion euros) and the US (21 billion euros).

The global turnover of the **ICT industry** is forecast to rise by 4.6 percent this year to 2.69 trillion euros. At 5.2 and 4.2 percent respectively, the two key segments of information technology and telecommunications are both experiencing strong growth. However, there are significant disparities in market trends across different regions. Whilst the industry is booming in newly-industrialised countries, throughout most of Western Europe it is either flat or in decline. Between them, **China, India and Russia** already account for one seventh (14 percent) of global ICT demand this year. The Chinese market alone is forecast to grow by 6.6 percent to 235 billion euros in 2013, overtaking Japan (221 billion euros) as the world's second largest ICT market. The **US** market remains the undisputed leader in terms of demand for ICT. The latest figures put its total value at 725 billion euros, an increase of 5.8 percent. Growth in **western Europe** has been more sluggish than in the rest of the world. In 2013, ICT sales are expected to rise by a modest 1.3 percent to 625 billion euros. The **German** information technology market, on the other hand, is forecast to grow by 3.0 percent in 2013 to 75 billion euros. Germany's software market is also set to experience strong growth, rising by 5.1 percent to 17.8 billion euros. The market for IT services such as outsourcing and maintenance is forecast to grow by 3.0 percent to 35.9 billion euros, whilst the hardware market is expected to return a modest growth figure of 1.2 percent.

With SAP, Software AG and Telekom, together with major subsidiaries of US (e.g. IBM and HP) and Asian companies, Germany has a globally significant level of IT competencies clustered closely together. This provides a new opportunity for Germany to take a leading role in Industrie 4.0.

Industrial policy funding initiatives in selected countries

Other countries are also supporting the modernisation of manufacturing industry through funding programmes and research initiatives. However, the available information suggests that in the US and China, for example, the transformation envisaged by the Industrie 4.0 initiative is regarded as no more than one trend among many, for example the introduction of new materials and technologies.[11]

US

The US administration has once again started to attach greater priority to the **mechanical engineering sector**.[12] It is now seeking to pursue an active industrial policy in order to create jobs and encourage reshoring of manufacturing to the US. In the summer of 2011, President Obama launched the Advanced Manufacturing Partnership (AMP), a private-sector led body that brings together representatives of the research, business and political communities to chart a "course for investing and furthering the development of the emerging technologies". The AMP Steering Committee is made up of the Presidents of the top engineering universities (MIT, UC Berkeley, Stanford, CMU, Michigan and GIT) and the CEOs of leading US enterprises (including Caterpillar, Corning, Dow Chemical, Ford, Honeywell, Intel, Johnson & Johnson, Northrop Grumman, Procter & Gamble and United Technologies).

In July 2012, the AMP submitted a report detailing 16 recommendations[13] which include the establishment of a National Network of Manufacturing Innovation Institutes (NNMII). These institutes, which take the form of Public-Private Partnerships, are intended to act as "regional hubs for manufacturing excellence" in order to improve the global competitiveness of US businesses and increase investment in US manufacturing facilities. [14]

In addition, the Obama administration is making more R&D funding available for manufacturing research. In the 2013 budget, the funding earmarked for advanced manufacturing is being increased by 19 percent to 2.2 billion dollars. On top of this, the National Institute of Standards and Technology (NIST), which is the body responsible for standardisation, has been allocated 100 million dollars of funding to provide technical support to domestic manufacturing industry through the provision of research facilities and know-how. NIST is also responsible for the Advanced Manufacturing Portal[15] which was set up at the AMP's recommendation and is intended to facilitate networking between government, university and private initiatives in this field. Finally, the US administration's Jobs and Innovation Accelerator Challenge initiative is investing 20 million dollars in a further ten Public-Private Partnerships in the field of advanced manufacturing.

CPS and the **Internet of Things** (IOT) have already been benefiting from public funding in the **US** for several years. Indeed, Cyber-Physical Systems were identified as a key research area by the National Science Foundation (NSF) as long ago as 2006. However, very little is actually being done with regard to the specific use of CPS in manufacturing.[16] The Networking and Information Technology Research and Development (NITRD) Programme brings together 18 research agencies in order to coordinate research in different IT domains including Human-Computer Interaction and Information Management. In 2011, the NITRD had a budget of over 3 billion dollars at its disposal.

China

China is also striving to expand its mechanical engineering industry. The 12th Five-Year Plan (2011-2015) sets out the aim of reducing dependency on foreign technology and pursuing global technology leadership in seven "strategic industries" including High-End Equipment Manufacturing and a New-Generation Information Technology[17]. China's leaders are making a total of 1.2 trillion euros available for this goal up to 2015 and are stimulating supply and demand through subsidies, tax breaks and other financial incentives. They also intend to increase R&D investment as a proportion of GDP from 1.5 to 2 percent by 2015.[18] In the **machine tools** sector, one of the priorities is the development of "intelligent manufacturing equipment", "intelligent control systems" and "high-class numerically controlled machines", whilst the priorities in the area of IT include the Internet of Things and its applications, including "industrial control and automation".

Since 2010, the priority attached by Beijing to the Internet of Things has grown significantly.[19] **China** has held an annual Internet of Things Conference since 2010 and China's first IoT Center was opened during the first of these conferences. This research centre has received 117 million US dollars worth of funding to investigate basic IoT technologies and the associated standardisation requirements. In addition, the School of Software at Dalian University of Technology established a research group as long ago as 2009 with a remit that includes the investigation of CPS applications in automation engineering. [20] China has also established an "IoT innovation zone" in the city of Wuxi in Jiangsu Province with 300 companies employing more than 70,000 people. China's leaders are planning to invest a total of 800 million US dollars in the IoT industry between now and 2015.[21]

EU

At **EU** level, research into the Internet of Things is currently benefiting from increased support through the Seventh Framework Programme for Research (2007-2013). The largest budgetary allocation of in excess of 9 billion euros is earmarked for the ICT funding priority. Within the programme, there are a variety of cross-border initiatives geared towards implementing the **Internet of Things** in **manufacturing industry.** The Siemens-led "IoT@Work" project has been given a budget of 5.8 million euros to develop the Plug&Work concept in a practical setting. Meanwhile, a total of 2.4 billion euros has been invested in the ARTEMIS technology platform to promote R&D projects in eight sub-programmes that include both "Manufacturing and Production Automation" and CPS.[22] In addition, 1.2 billion euros have been awarded to the Public-Private Partnership initiative "Factories of the Future" which launches annual calls for proposals for projects in the area of smart, ICT-driven manufacturing. Under the auspices of this initiative, the SAP-led project "ActionPlanT" recently submitted its "Vision for Manufacturing 2.0", that is intended to serve as a discussion document for future research funding initiatives under the Eighth Framework Programme for Research – "Horizon 2020" (2014-2020). Horizon 2020's proposed budget of 80 billion euros will make it the world's largest R&D funding programme.[23]

India

Innovation funding is one of the core priorities of **India's** Five-Year Plan (2012-2017) which provides for an increase in public and private R&D investment to two percent of GDP.[24] In 2011, the "**Cyber-Physical Systems** Innovation Hub" project was launched under the auspices of the Ministry of Communications and Information Technology to conduct research into a variety of areas, including humanoid robotics. Moreover, Bosch founded the Centre for Research in CPS in Bangalore in November 2011. Both the Fraunhofer-Gesellschaft and several top Indian research centres are participating in this project in an advisory capacity. The partnership, which is funded to the tune of 22.8 billion euros, aims to create an optimal research and working environment for the IT specialists of the future. In future, support will also be provided to industry and the research community, for example through research contracts.[25] Even today, according to a recent study by the Zebra Tech Company, Indian businesses are world leaders in terms of take-up and use of IoT technology.[26]

TAKE-HOME MESSAGE

Many of Germany's competitors have also recognised the trend for using the Internet of Things in the manufacturing environment and are promoting it through a range of institutional and financial measures. The Industrie 4.0 Working Group believes that Germany is well placed to become a global pacesetter in the area of Industrie 4.0. The Industrie 4.0 Platform should undertake regular critical appraisals of the extent to which the measures implemented and planned by Germany are succeeding in delivering this goal.

A separate research project should be established to carry out a more detailed analysis of Germany's international competitors and the markets it should be targeting over the next ten to 15 years.

1 At the end of 2012, US-based company General Electric (GE) publicly launched a broad-based initiative focused on the Internet of Things (IoT). Although GE's "Industrial Internet" strategy has applications in a huge variety of different areas, manufacturing only plays a minor role. GE believes that there is potential to deliver significant global savings through deployment of the IoT in a range of different industries. It calculates that fuel consumption in the commercial air travel sector could be cut by 1 percent over 15 years, generating savings of 30 billion dollars, whilst efficiency gains in the healthcare and freight and rail transport industries could save 66 billion and 27 billion dollars respectively. (See Evans, Peter C./Annunziata, Marco: Industrial Internet. Pushing the Boundaries of Minds and Machine (GE Study), November 2012, p. 4)

2 For details on how this term is used, see e.g. Evans, Peter C./Annunziata, Marco: Industrial Internet. Pushing the Boundaries of Minds and Machine (GE study), November 2012, p. 7f.

3 This is the reasoning underpinning the statement made by the European Commissioner for Industry and Entrepreneurship, Antonio Tajani, when he proclaimed a third Industrial Revolution in May 2012 (see European Commission: Building a New Industrial Revolution in Europe. In: Unternehmen und Industrie Magazin, June 2012.). A few months later, following a public consultation, Tajani identified six key areas that should be strengthened in the future by the EU, the member states and private actors. Two of these areas are directly relevant to Industrie 4.0: the promotion of "advanced manufacturing technologies" and "key enabling technologies" (see European Commission: Industrial revolution brings industry back to Europe (press release), 10 October 2012).

4 To some extent, the discourse surrounding the third Industrial Revolution is also connected with a new innovation cycle characterised by the use and expansion of renewable energy (see e.g. Rifkin, Jeremy: The Third Industrial Revolution: How Lateral Power Is Transforming Energy, the Economy, and the World, 2011), a dramatic increase in resource productivity and the use of new materials, substances and processes (e.g. 3D printing; see Hill, Jürgen: Das Potential von 3D-Druck, in: Computerwoche, 29.01.2013).

5 See e.g. the blog smartmanufacturing.com or the initiative Smart Manufacturing Leadership Coalition (SMLC), more information available online at www.smartmanufacturingcoalition.org.

6 Advanced manufacturing is a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies." This definition, which was produced by the President's Council of Advisors on Science and Technology (PCAST), one of the US administration's most important advisory committees on technology trends, is typical of how this particular term is used (see PCAST: Report to the President on Ensuring American Leadership in Advanced Manufacturing, June 2011, p. ii).

7 A total of 483 companies participated in the VDMA survey (see VDMA: Tendenzbefragung. Internationale Wettbewerbsposition des deutschen Maschinen- und Anlagebaus [Survey of Current Trends. Global Competitive Position of German Machinery and Plant Manufacturers], October 2012).

8 See Le Monde Diplomatique: Die Zukunft der Industrie liegt in Asien, in: Atlas der Globalisierung – Die Welt von morgen, 2012, p. 28.

9 See Minter, Steve: Evidence for U.S. Manufacturing Reshoring Builds. In: The Global Manufacturer, October 2012, and The Economist: Reshoring manufacturing. Coming home, Special Report, January 2012.

10 See Fishman, Charles: The Insourcing Boom. The Atlantic, December 2012.

11 See, for example, McKinsey Global Institute: Manufacturing the future: The next era of global growth and innovation, November 2012.

12 This is at least partly in response to calls made by the Association for Manufacturing Technology and the recommendations of the President's Council of Advisors on Science and Technology (PCAST). In its 2012 report on "Capturing Domestic Competitive Advantage in Advanced Manufacturing", PCAST, which advises the US administration, argued that the US is losing its position as a leading manufacturing nation and, unlike other industrialised nations, is doing hardly anything about it at a policy level.

13 PCAST: Capturing Domestic Competitive Advantage in Advanced Manufacturing. AMP Steering Committee Report, July 2012; see also National Science and Technology Council (NSTC): National Strategic Plan for Advanced Manufacturing, February 2012.

14 The network is currently under development. Funding from a number of US State administrations and businesses will be complemented by a one billion dollar investment on behalf of central government. The aim is to establish a total of 15 research institutes that will focus on different aspects of advanced manufacturing. This is intended to improve coordination between university research and product development within enterprises (see also Appendix 1: Technology Development Workstream Report, in: PCAST: Capturing Domestic Competitive Advantage in Advanced Manufacturing. AMP Steering Committee Report, July 2012).

15 Online at: www.manufacturing.gov.

16 Of the 108 projects since 2008 that have received funding of between 500,000 and 1 million dollars, it appears that only one is specifically focused on the use of CPS in manufacturing.

17 In these areas, the Plan speaks emphatically of "leapfrogging".

18 This would bring China's R&D expenditure up to around 215 billion euros by 2015, or roughly three times the amount that Germany currently spends on research and development (see Nürnberg, Jörg/Wang, Thomas: Implications of the 12th Five Year Plan For German Machinery Manufacturers, April 2012).

19 Since 2010, outgoing premier Wen Jiabao has set out the importance of the IoT as a key technology for China's development in several speeches. The Minister of Industry and Information Technology, Li Yizhong, also highlighted this topic in an article entitled "We must make use of information technology to restructure and improve traditional industry; we should formulate policies to encourage the development of Internet of Things" (see http://en.cbf.net.au/Item/639.aspx - last visited by the authors in January 2013).

20 See Geisberger, Eva/Broy, Manfred: agendaCPS. Integrierte Forschungsagenda Cyber-Physical Systems (agendaCPS. Integrated Research Agenda Cyber-Physical Systems) (acatech STUDY), Heidelberg et al.: Springer Verlag 2012.

21 See Voigt, Kevin: China looks to lead the Internet of Things, (CNN), 28 November 2012.

22 Since 2008, ARTEMIS has also been organising an annual worldwide "CPS week". The European Research Cluster on the Internet of Things (IERC) is an initiative funded through the Seventh Framework Programme for Research which coordinates European research activities in this area.

23 In the UK, a group of experts is currently studying the future of manufacturing. "The Future of Manufacturing" project will identify potential development strategies for manufacturing up to 2050.

24 See Government of India, Planning Commission: Faster, Sustainable and More Inclusive Growth. An Approach to the Twelfth Five Year Plan, October 2011, p. 115.

25 See Geisberger, Eva/Broy, Manfred: agendaCPS. Integrierte Forschungsagenda Cyber-Physical Systems (agendaCPS. Integrated Research Agenda Cyber-Physical Systems) (acatech STUDY), Heidelberg et al.: Springer Verlag 2012.

26 See CXO today News Desk: Indian CIOs keen on adopting Internet of Things, 11 October 2012.

EXAMPLE APPLICATION 5: Sudden change of supplier during production due to a crisis beyond the manufacturer's control

Circumstances beyond the manufacturer's control, such as unexpected natural disasters or political crises, mean that they often have to change suppliers suddenly during production. Industrie 4.0 can help to make these changes substantially smoother by running simulations of the affected downstream services, thus allowing different suppliers to be evaluated and the best alternative to be selected.

Today

In the event of unexpected supplier failure, it is currently difficult for manufacturers to assess the impact on current production and downstream processes and come up with a timely response. Sudden supplier failures result in significant additional costs and delays in production and thus entail major risks to companies' business. They need to take quick decisions about which alternative supplier to use as cover, how to execute the logistics for goods that are currently in production, how long current stocks are likely to last, which products already contain components from the failed supplier and whether the alternative suppliers actually have the ability and skills needed to provide the required capacity by the relevant deadline. Currently, it is only possible to provide partial IT support for these decisions.

Tomorrow

In Industrie 4.0 it will be possible to simulate all the steps in the manufacturing process and depict their influence on production. This will include simulation of inventory levels, transport and logistics, the ability to track the usage history of components that have already been used in production and provision of information relating to how long components can be kept before they expire. This will enable product-specific set-up costs to be calculated and reconfiguration of production resources to be kept to a minimum. It will also be possible to assess the relevant risks. It will thus be possible to simulate the different costs and margins of alternative suppliers, including simulation of the environmental impact associated with using one supplier over another. Extensive networking of manufacturing systems will make it possible to analyse alternative suppliers and their capacity in real time.
It will be possible to contact and engage suppliers directly via the appropriate secure channels in the supplier cloud.

POTENTIAL BENEFITS

IT innovations such as Big Data and the Cloud allow real-time optimised simulations to be performed. The necessary software designs already exist. The value drivers in favour of prompt implementation of this approach include time and cost savings and the ability to minimise risks to the business.

7 Outlook

7 Outlook

Germany has the potential to become a leading market and leading supplier for Industrie 4.0. If this is to be achieved then, in addition to meeting the technological challenges, it will be essential for the different industries and their employees to work together in order to shape developments. The Industrie 4.0 Platform constitutes a crucial step towards ensuring that the innovation potential of Industrie 4.0 is leveraged across all industries.

The journey towards implementing the Industrie 4.0 vision will involve an evolutionary process that will progress at different rates in individual companies and sectors. Demonstration projects should therefore be developed and new products brought to market as soon as possible.

Implementation should be addressed through a dual strategy. Existing basic technologies and experience will need to be adapted to the requirements of manufacturing engineering and rolled out rapidly on a widespread basis. At the same time, it will also be necessary to research and develop innovative solutions for new manufacturing sites and new markets. If this is done successfully, Germany will be in a position to become a leading supplier for Industrie 4.0. Moreover, the establishment of a leading market will serve to make Germany a more attractive manufacturing location and help preserve its domestic manufacturing industry.

The Industry-Science Research Alliance launched the strategic initiative Industrie 4.0 in early 2011. As of April 2013, the industry's professional associations BITKOM, VDMA and ZVEI will be joining together with actors from the business and research communities and civil society in order to ensure that implementation of the initiative is progressed in a coherent manner. A systemic approach in which all the stakeholders are involved in a mutual exchange of technological and social innovations will provide a sound basis for successful cooperation in this regard.

The strategic initiative Industrie 4.0

The strategic initiative Industrie 4.0

Industrie 4.0 is a "strategic initiative" of the German government that was adopted as part of the High-Tech Strategy 2020 Action Plan in November 2011. It was launched in January 2011 by the COMMUNICATION Promoters Group of the Industry-Science Research Alliance (FU). Its initial implementation recommendations were formulated by the **Industrie 4.0 Working Group** between January and October 2012 under the coordination of acatech –National Academy of Science and Engineering. The Working Group was chaired by Dr Siegfried Dais, Deputy Chairman of the Board of Management of Robert-Bosch GmbH, and Prof. Henning Kagermann, President of acatech. The recommendations were submitted as a report to the German government at the Industry-Science Research Alliance's Implementation Forum held at the Produktionstechnisches Zentrum Berlin on 2 October 2012. Going forward, further implementation measures will be progressed through a number of working groups under the Industrie 4.0 Platform which was recently established by the industry's professional associations BITKOM, VDMA and ZVEI and which now has the support of its own Secretariat.

Since 2006, the German government has been pursuing a High-Tech Strategy geared towards interdepartmental coordination of research and innovation initiatives in Germany with the aim of securing Germany's strong competitive position through technological innovation. The current incarnation is known as the High-Tech Strategy 2020 and focuses on five priority areas: climate/energy, health/food, mobility, security and communication. The strategy revolves around a number of "strategic initiatives" through which the Industry-Science Research Alliance is addressing concrete medium-term scientific and technological development goals over a period of ten to fifteen years. The initiatives have formulated concrete innovation strategies and implementation roadmaps designed to make Germany a leader in supplying solutions to global challenges.

This report presents and expands upon the recommendations put forward by the Industrie 4.0 Working Group in October 2012 and will provide a basis for the work of the Industrie 4.0 Platform that will commence in April 2013

Home page of the Industry-Science Research Alliance:
forschungsunion.de

High-Tech Strategy Action Plan available at:
bmbf.de/pub/HTS-Aktionsplan.pdf

Industrie 4.0 Working Group reports:
acatech.de/industrie4.0

The Industrie 4.0 Platform

The professional associations BITKOM, VDMA and ZVEI have established the joint Industrie 4.0 Platform in order to progress the initiative and ensure a coordinated, cross-sectoral approach.

The Platform's central coordination and management body is the industry-led **Steering Committee.** It is responsible for setting the Platform's strategic course, appointing working groups and guiding their work. The Steering Committee is supported by a **Scientific Advisory Committee** that includes members from the manufacturing, IT and automation industries as well as a number of other disciplines. The **Working Groups** report to the Steering Committee, but are free to determine their own structure. They are open to all interested parties.

The **Governing Board** provides input with regard to strategy and supports the Platform's political activities. Where necessary, it represents the Platform vis-à-vis policymakers, the media and the public.

The **Secretariat** is staffed by members of the three professional associations and provides the Steering Committee with organisational and administrative support. It deals with knowledge transfer, internal relations and relations with similar initiatives. It is also responsible for media and public relations activities.

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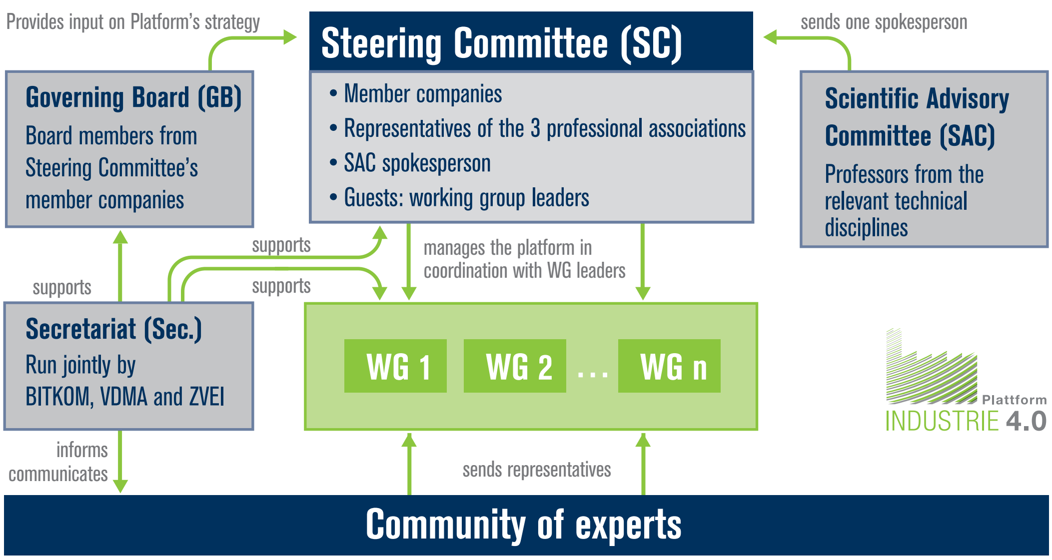
Figure 14: Provisional organisational chart of the "Industry 4.0" Platform



Plattform
INDUSTRIE 4.0

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Research Letters

Recent advances and trends in predictive manufacturing systems in big data environment

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Abstract

The globalization of the world's economies is a major challenge to local industry and it is pushing the manufacturing sector to its next transformation – predictive manufacturing. In order to become more competitive, manufacturers need to embrace emerging technologies, such as advanced analytics and cyber-physical system-based approaches, to improve their efficiency and productivity. With an aggressive push towards "Internet of Things", data has become more accessible and ubiquitous, contributing to the big data environment. This phenomenon necessitates the right approach and tools to convert data into useful, actionable information.

Keywords: Predictive Manufacturing; Big Data; Manufacturing; Prognostics and Health Management; PHM; CPS; Cyber-physical Systems; Analytics

1. Manufacturing definition and trends

Manufacturing can be described as a 5M system which consists of Materials (properties and functions), Machines (precision and capabilities), Methods (efficiency and productivity), Measurements (sensing and improvement), and Modeling (prediction, optimization, and prevention). Additive manufacturing is a new paradigm for creating products using an integrated 5M approach but is limited to certain applications with low-volume or customized (such as defense or medical) applications.

To make manufacturers more competitive, there is a need to integrate advanced computing and cyber-physical systems to adapt to, as well as take advantage of, the current big data environment. With the advent of smart sensors such as RFID technologies, collecting data has become a simple exercise, but the question remains if these devices or data provide the right information for the right purpose at the right time. Data is not useful unless it is processed in a way that provides context and meaning that can be understood by the right personnel. Just connecting sensors to a machine or connecting a machine to another machine will not give users the insights needed to make better decisions. The basic definition of a manufacturing information system can be further enhanced with a 5C functions, which consist of Connection (sensor and networks), Cloud (data on demand and anytime), Content (correlation and meaning), Community (sharing and social), and Customization (personalization and value). Current manufacturing systems require deeper analysis of various data from machines and processes. For example, traditional overall equipment effectiveness (OEE) only provides the status of production efficiency [1]. It does not paint a clear view of the relationship between performance and the cost involved in sustaining a certain OEE level. Furthermore, machine condition data is not correlated with controller and inspection data to distinguish between process and machine degradation.

2. Productivity transformation: the visible and invisible opportunities

Generally, manufacturing issues can be mapped into two spaces (see Figure 1): visible and invisible. Some

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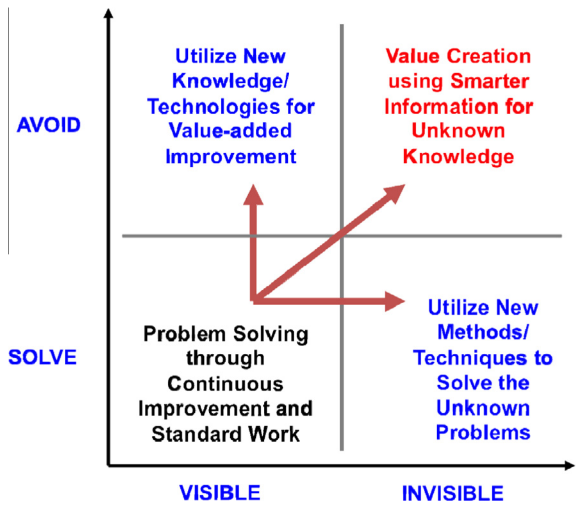

Figure 1. Productivity Opportunity Spaces.

examples of visible issues include machine failure, product defects, poor cycle times, time delays, drop in (OEE), etc. Invisible issues may occur, such as machine degradation, component wear, lack of lubrication, etc. In each of these spaces, issues are treated in both deterministic and uncertain levels. The traditional manufacturing space (lower left space) depicts problem solving for well-defined problems such as quality, productivity, and costs issues, etc., through continuous improvement, best practices, and standard work. Competitive manufacturers use new methods and technologies to work with their suppliers and partners to integrate design and manufacturing for problem avoidance (upper left space). For example, advanced modeling and simulation have been used to avoid poor porosity in super alloy casting process to eliminate cracks due to thermal flight during welding. Many companies have also developed new methods and techniques for the unknown problems and further provide value-added solution to their customers (lower right space). Examples include GE Aviation's On-Wing Support Smart Engine Service for reducing maintenance costs, and John Deere's Agri Service for providing farmers with crop yield management beyond farming equipment. Current efforts in cyber-physical system-based approach will produce many new value-creation opportunities for future manufacturing (upper right space) [2]. A NIST-sponsored workshop has defined cyber-physical systems as consisting of computational and physical components, seamlessly and closely integrated to perceive changes in the real system [3]. For example, (a) future machines will have a twin (an Avatar) integrated in both the physical and cyber spaces; (b) self-aware sensors can perceive changes in machine behavior with precision meaning; and (c) machines can form communities to enable peer-to-peer comparison [4].

Manufacturing companies employ continuous improvement through waste reduction (greener) and work reduction (leaner) for enhanced operations. Yet, there are still many invisible issues and uncertainties (worry) in manufacturing that can exist both internal and external to the factory. Examples of internal issues include degradation of machine and the manufacturing processes and the occurrence of failure events without any recognizable symptoms (component level); variation of cycle time due to inconsistent operation, unplanned breakdown of systems and the presence of scraps and rework that disrupt normal production planning and scheduling (system or production process level). Meanwhile, external uncertainties, typically stemming from product development all the way through the supply chain, can manifest as: (1) unreliable downstream capacity, (2) unpredictable variation of raw materials or parts in terms of delivery, quantity and quality, (3) market and customer demand fluctuation, and (4) incomplete product design due to the lack of accurate estimation of product state during production and usage, among others. These invisible worries and uncertainties have adverse effects in manufacturing if there are no predictive analytics and control strategies implemented. New, smarter technologies are needed for worry reduction to make manufacturing more transparent.

3. Predictive manufacturing systems in big data environment: needs and technologies

Transparency is the ability of an organization to unravel and quantify uncertainties to determine an objective estimation of its manufacturing capability and readiness [5]. Most manufacturing strategies assume continuous equipment availability and constant optimal performance, however, this is never the case in a real factory. In order to achieve transparency, the manufacturing industry has to transform itself into predictive manufacturing. Such evolution requires the utilization of advanced prediction tools so that data can be systematically processed into information that can explain the uncertainties and thereby enable personnel to make more informed decisions. The aggressive adoption of the "Internet of Things" ideology has helped in laying the foundation for predictive manufacturing by setting the essential structures of smart sensor networks and smart machines [6]. The goal of a predictive manufacturing system is to enable machines and systems with "self-aware" capabilities. The core technology is the smart computational agent that contains smart software to conduct predictive modeling functionalities [2].

Prognostics and health management (PHM) is a critical research domain that leverages on advanced predictive tools. Insights into future equipment performance and estimation of the time to failure will reduce the impacts of these uncertainties, and give users the opportunity to proactively implement solutions to prevent performance loss of the manufacturing system.

The conceptual framework of a predictive manufacturing system (see Figure 2) starts with data acquisition from the monitored assets. Using appropriate sensor installations, various signals such as vibration, pressure, etc. can be extracted. In addition, historical data can be harvested

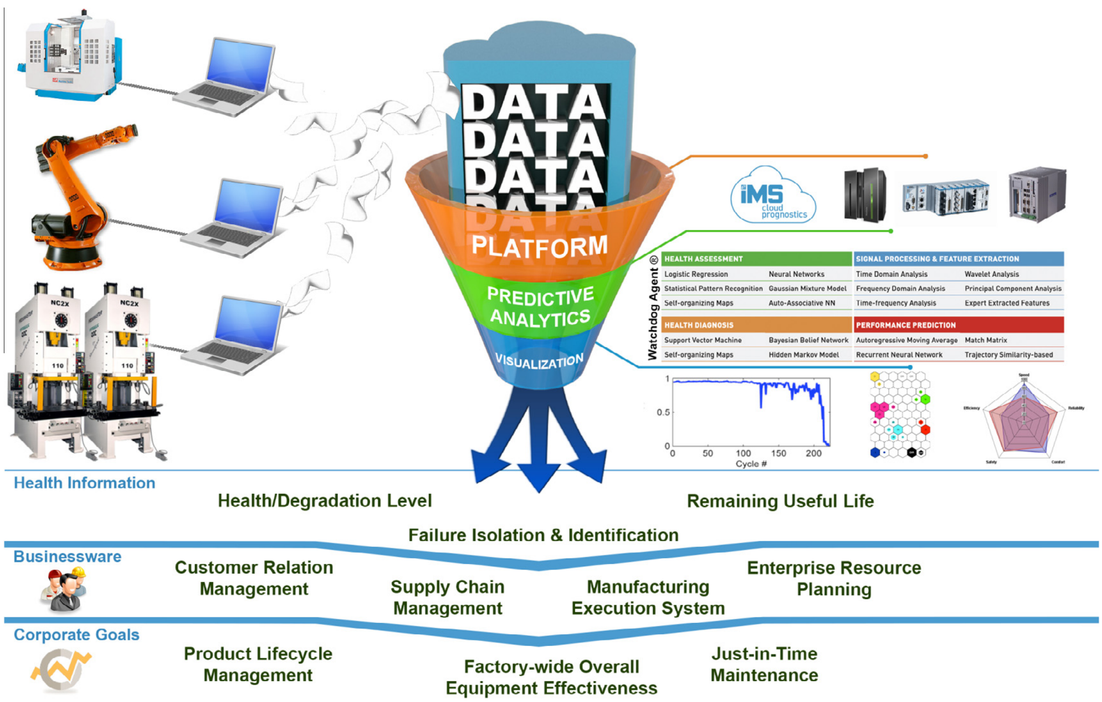

Figure 2. Predicting manufacturing system framework using Watchdog Agent® predictive analytics.

for further data mining. Communication protocols, such as MTConnect [7] and OPC, can help users to record controller signals. When all the data are aggregated, this amalgamation is called “Big Data”. The transforming agent consists of several components: an integrated platform, predictive analytics and visualization tools. The deployment platform is chosen based on: speed of computation, investment cost, ease of deployment and update, etc. The actual processing of big data into useful information is performed by predictive analytics such as the Watchdog Agent® that has been developed by the Center for Intelligent Maintenance Systems (IMS) since 2001 [8,9]. The algorithms found in the Watchdog Agent® can be categorized into four sections: signal processing and feature extraction,

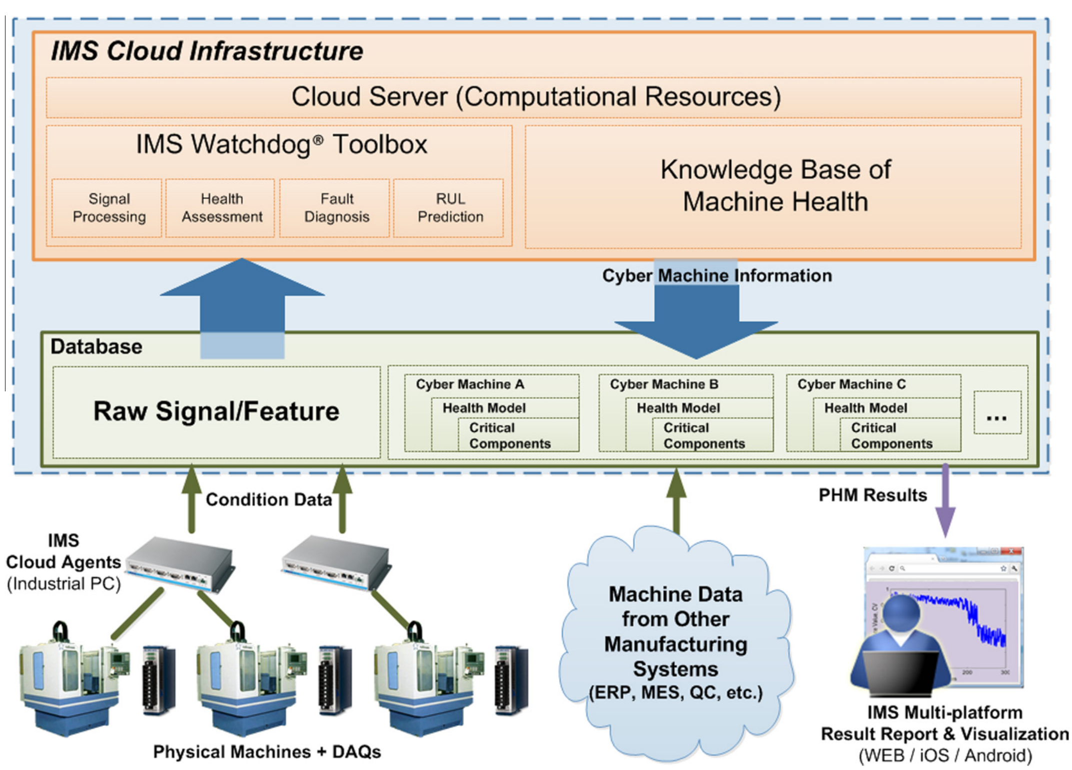

Figure 3. Cyber-physical model for enhanced predictive manufacturing system.

health assessment, performance prediction, and fault diagnosis. By utilizing visualization tools, health information (such as current condition, remaining useful life, failure mode, etc.) can be effectively conveyed in a radar chart, fault map, risk chart, or by health degradation curves. The calculated health information can be made accessible to existing company management systems (ERP, MES, SCM and CRM system), to achieve enterprise control and optimization. With manufacturing transparency, management then has the right information to determine facility-wide OEE. With the prediction capability, equipment can be managed cost effectively with just-in-time maintenance. Finally, historical health information can be fed back to the equipment designer for closed loop lifecycle redesign.

4. Cyber-physical models for future manufacturing

Current PHM implementations mostly utilize data during actual usage while analytical algorithms can perform more accurately when more information throughout the machine's lifecycle, such as system configuration, physical knowledge and working principles, are included. There is a need to systematically integrate, manage and analyze machinery or process data during different stages of machine life cycle to handle data/information more efficiently and further achieve better transparency of a machine's health condition for the manufacturing industry.

With such motivation, a cyber-physical (coupled) model scheme has been developed and is illustrated in Figure 3. The coupled model is a digital twin of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge. It can also be described as a 5S systematic approach consisting of Sensing, Storage, Synchronization, Synthesis and Service. The coupled model first constructs a digital image from the early design stage. System information and physical knowledge are logged during product design, based on which a simulation model is built as a reference for future analysis. Initial parameters may be statistically generalized and can be tuned using data from testing or the manufacturing process using parameter estimation. The simulation model can then be considered a mirror image of the real machine, which is able to continuously record and track machine condition during the later utilization stage. Finally, with ubiquitous connectivity offered by cloud computing technology, the coupled model also provides better accessibility of machine condition for factory managers for cases in which physical access to actual equipment or machine data is limited.

References

[1] Lee J, Lapira E. TPM gets smart. Manuf. Eng. June 2011;156(6):70–5.

[2] Lee J, Lapira E, Yang S, Kao, HA. Predictive manufacturing system trends of next generation production systems. In: the Proceedings of the 11th IFAC workshop on intelligent manufacturing systems, vol. 11(1); 2013. p. 150–156.

[3] National Institute of Standards and Technology. Workshop report on foundations for innovation in cyber-physical systems. January 2013. Available from: <http://www.nist.gov/el/upload/CPS-WorkshopReport-1-30-13-Final.pdf>.

[4] Lapira E. (2012) Fault detection in a network of similar machines using clustering approach. (Doctoral Dissertation). 2012. Retrieved from: <https://etd.ohiolink.edu/>.

[5] Lee J, Lapira E. Predictive factories: the next transformation. Manufacturing leadership journal. Frost Sullivan; 2013.

[6] Chui M, Loffler M, Robert R. The internet of things. mckinsey quarterly No. 2; 2010.

[7] MTConnect Institute. MTConnect Overview. Retrieved on September 4, 2013. <http://www.mtconnect.org/overview/mtconnect-overview.aspx>.

[8] Lee J, Ni J, Djurdjanovic D, Qui H, Liao H. Intelligent prognostics tools and e-maintenance. Comput Ind 2006;57(6):476–89.

[9] Lee J, Wu F, Zhao W, Ghaffari M, Liao L, Siegel D. Prognostics and health management design for rotary machinery systems – reviews, methodology and applications. Mech Systems and Signal Proc; 2013. Article in Press. <http://www.sciencedirect.com/science/article/pii/S0888327013002860>.

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Research Letters

A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems

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Abstract

Recent advances in manufacturing industry has paved way for a systematical deployment of Cyber-Physical Systems (CPS), within which information from all related perspectives is closely monitored and synchronized between the physical factory floor and the cyber computational space. Moreover, by utilizing advanced information analytics, networked machines will be able to perform more efficiently, collaboratively and resiliently. Such trend is transforming manufacturing industry to the next generation, namely Industry 4.0. At this early development phase, there is an urgent need for a clear definition of CPS. In this paper, a unified 5-level architecture is proposed as a guideline for implementation of CPS.

Keywords: Cyber-Physical System; Industry 4.0; Health management and prognostics; Time machine

1. Introduction

Cyber-Physical Systems (CPS) is defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities [1]. With recent developments that have resulted in higher availability and affordability of sensors, data acquisition systems and computer networks, the competitive nature of today's industry forces more factories to move toward implementing high-tech methodologies. Consequently, the ever growing use of sensors and networked machines has resulted in the continuous generation of high volume data which is known as Big Data [2,3]. In such an environment, CPS can be further developed for managing Big Data and leveraging the interconnectivity of machines to reach the goal of intelligent, resilient and self-adaptable machines [4,5]. Furthermore by integrating CPS with production, logistics and services in the current industrial practices, it would transform today's factories into an Industry 4.0 factory with significant economic potential [6,7]. For instance, a joint report by the Fraunhofer Institute and the industry association Bitkom said that German gross value can be boosted by a cumulative 267 billion euros by 2025 after introducing Industry 4.0 [8]. A brief comparison between current and Industry 4.0 factories is presented in Table 1 [9].

Since CPS is in the initial stage of development, it is essential to clearly define the structure and methodology of CPS as guidelines for its implementation in industry. To meet such a demand, a unified system framework has been designed for general applications. Furthermore, corresponding algorithms and technologies at each system layer are also proposed to collaborate with the unified structure and realize the desired functionalities of the overall system for enhanced equipment efficiency, reliability and product quality.

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2. CPS 5C level architecture

The proposed 5-level CPS structure, namely the 5C architecture, provides a step-by-step guideline for developing and deploying a CPS for manufacturing application. In general, a CPS consists of two main functional components: (1) the advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space; and (2) intelligent data management, analytics and computational capability that constructs the cyber space. However, such requirement is very abstract and not specific enough for implementation purpose in general. In contrast, the 5C architecture presented here clearly defines, through a sequential workflow manner, how to construct a CPS from the initial data acquisition, to analytics, to the final value creation. As illustrated in Fig. 1, the detailed 5C architecture is outlined as follows:

2.1. Smart connection

Acquiring accurate and reliable data from machines and their components is the first step in developing a Cyber-Physical System application. The data might be directly measured by sensors or obtained from controller or enterprise manufacturing systems such as ERP, MES, SCM and CMM. Two important factors at this level have to be considered. First, considering various types of data, a seamless and tether-free method to manage data acquisition procedure and transferring data to the central server is required where specific protocols such as MTConnect [10] and etc. are effectively useful. On the other hand, selecting proper sensors (type and specification) is the second important consideration for the first level.

2.2. Data-to-information conversion

Meaningful information has to be inferred from the data. Currently, there are several tools and methodologies available for the data to information conversion level. In recent years, extensive focus has been applied to develop these algorithms specifically for prognostics and health management applications. By calculating health value, estimated remaining useful life and etc., the second level of CPS architecture brings self-awareness to machines (Fig. 2).

Table 1
Comparison of today's factory and an Industry 4.0 factory.

	Data source	Today's factory		Industry 4.0	
		Attributes	Technologies	Attributes	Technologies
Component	Sensor	Precision	Smart sensors and fault detection	Self-aware Self-predict	Degradation monitoring & remaining useful life prediction
Machine	Controller	Producibility & performance	Condition-based monitoring & diagnostics	Self-aware Self-predict Self-compare	Up time with predictive health monitoring
Production system	Networked system	Productivity & OEE	Lean operations: work and waste reduction	Self-configure Self-maintain Self-organize	Worry-free productivity

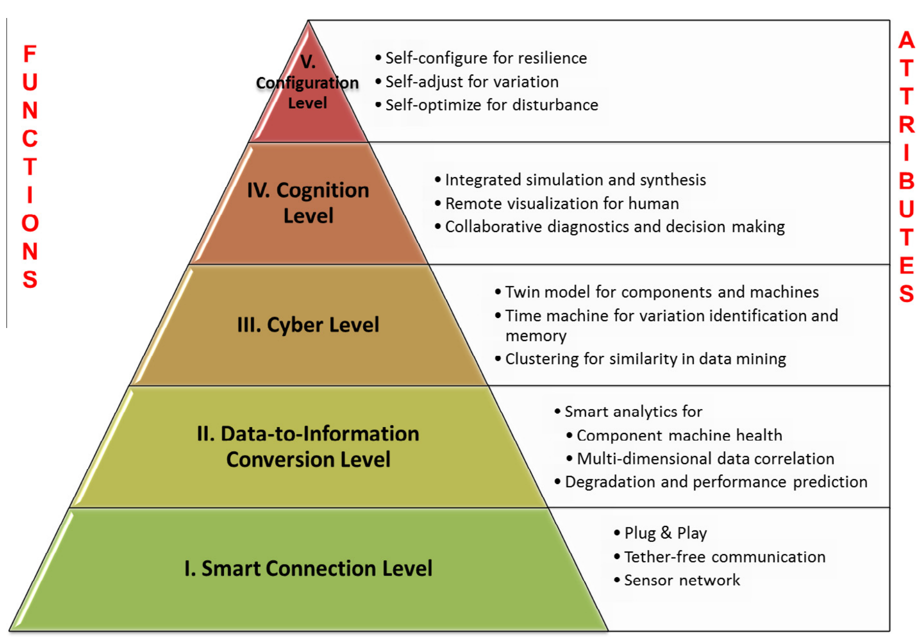

Fig. 1. 5C architecture for implementation of Cyber-Physical System.

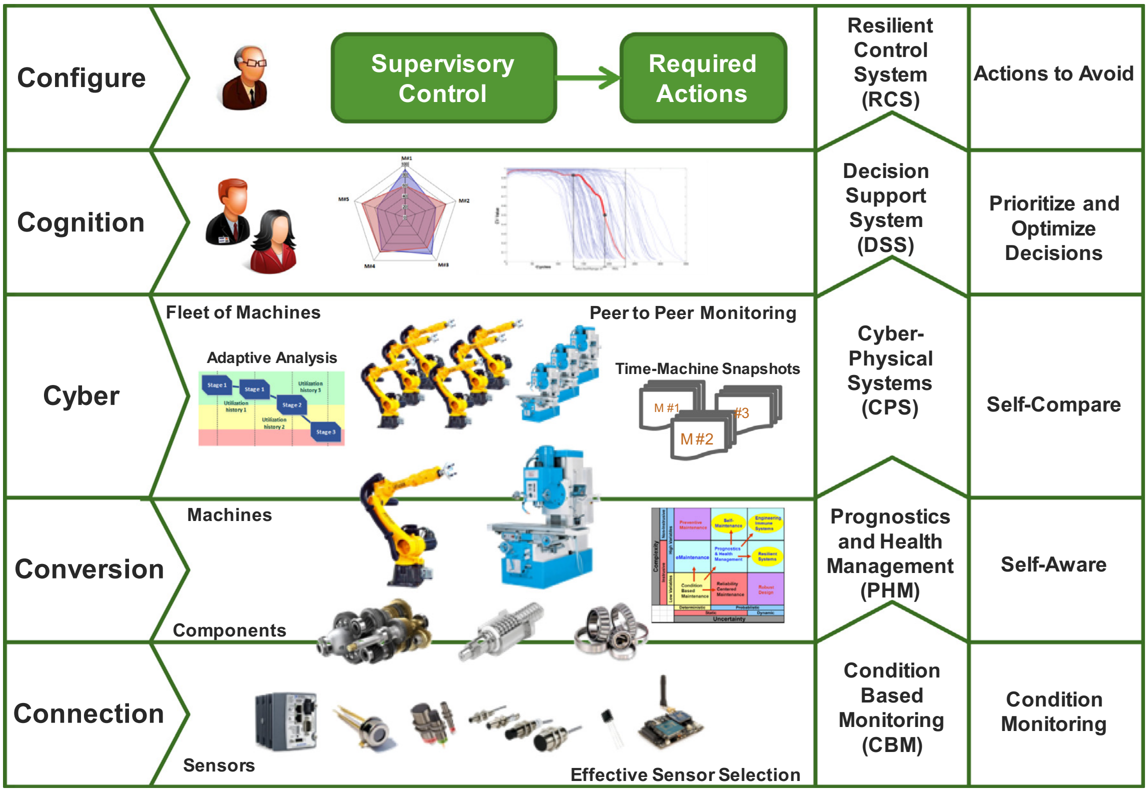

Fig. 2. Applications and techniques associated with each level of the 5C architecture.

2.3. Cyber

The cyber level acts as central information hub in this architecture. Information is being pushed to it from every connected machine to form the machines network. Having massive information gathered, specific analytics have to be used to extract additional information that provide better insight over the status of individual machines among the fleet. These analytics provide machines with self-comparison ability, where the performance of a single machine can be compared with and rated among the fleet. On the other hand, similarities between machine performance and previous assets (historical information) can be measured to predict the future behavior of the machinery. In this paper, we briefly introduce an efficient yet effective methodology for managing and analyzing information at cyber level (Section 3).

2.4. Cognition

Implementing CPS upon this level generates a thorough knowledge of the monitored system. Proper presentation of the acquired knowledge to expert users supports the correct decision to be taken. Since comparative information as well as individual machine status is available, decision on priority of tasks to optimize the maintaining process can be made. For this level, proper info-graphics are necessary to completely transfer acquired knowledge to the users.

2.5. Configuration

The configuration level is the feedback from cyber space to physical space and acts as supervisory control to make machines self-configure and self-adaptive. This stage acts as resilience control system (RCS) to apply the corrective and preventive decisions, which has been made in cognition level, to the monitored system.

3. Design of PHM based CPS systems

The extreme advantage of cyber level PHM is the interconnection between machine health analytics through a machine–cyber interface (CPI) at the cyber level, which is conceptually similar to social networks. Once the cyber-level infrastructure is in place, machines can register into the network and exchange information through cyber-interfaces. At this point, an algorithm has to be established to track the changes of a machine status, infer additional knowledge from historical information, apply peer-to-peer comparison and pass the outputs to the next level. New methods have to be developed to perform these actions and generate appropriate results. In this paper, we introduce the “time machine” that performs analytics at the cyber level and consists of three parallel sections as follows.

I. *Snapshot collection:* As illustrated in Fig. 3, information is continuously being pushed to the cyber space from machines. The role of snapshot collection is to

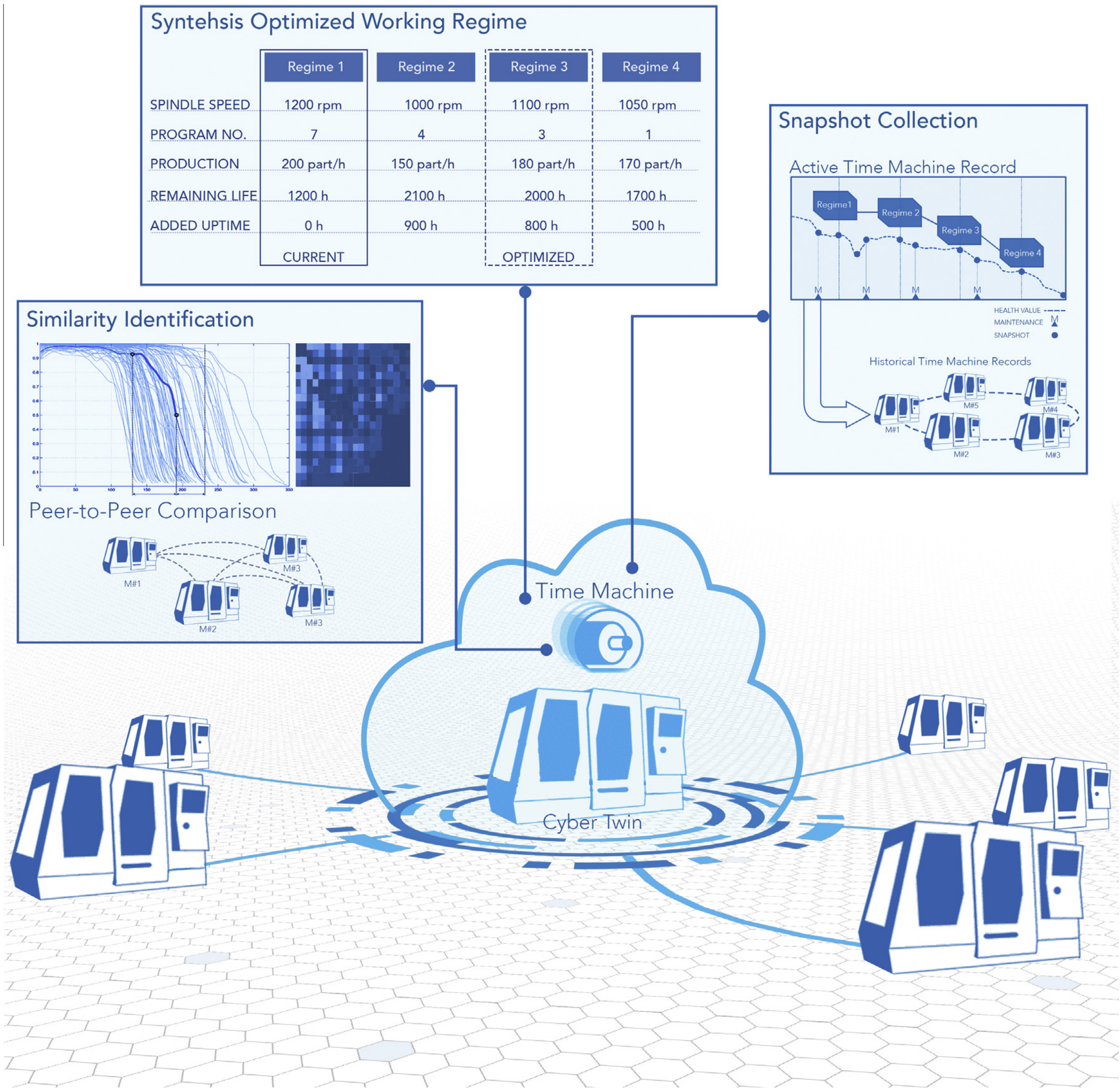

Fig. 3. Time machine approach for Cyber-Physical PHM.

manage the incoming data and store the information in an efficient fashion. Basically, to reduce required disk space and process power, snapshots of machine performance, utilization history and maintenance has to be recorded instead of the whole time-series. These snapshots are only taken once a significant change has been made to the status of the monitored machine. The change can be defined as dramatic variation in machine health value, a maintenance action or a change in the working regime. During the life cycle of a machine, these snapshots will be accumulated and used to construct the time-machine history of the particular asset. This active time-machine record will be used for peer-to-peer comparison between assets. Once the asset is failed or replaced, its relative time-machine record will change status from active to historical and will be used as similarity identification and synthesis reference.

II. *Similarity identification:* In cyber level, due to availability of information from several machines, the likelihood of capturing certain failure modes in a shorter time frame is higher. Therefore, the similarity identification section has to look back in historical time machine records to calculate the similarity of current machine behavior with former assets utilization and health. At this stage, different algorithms can be utilized to perform pattern matching such as match matrix, trajectory similarity method [11] or various stochastic methods. Once the patterns are matched, future behavior of the monitored system can be predicted more accurately.

III. *Synthesis optimized future steps:* Predicting remaining useful life of assets helps to maintain just-in-time maintenance strategy in manufacturing plant. In addition, life prediction along with historical time machine records can be used to improve the asset

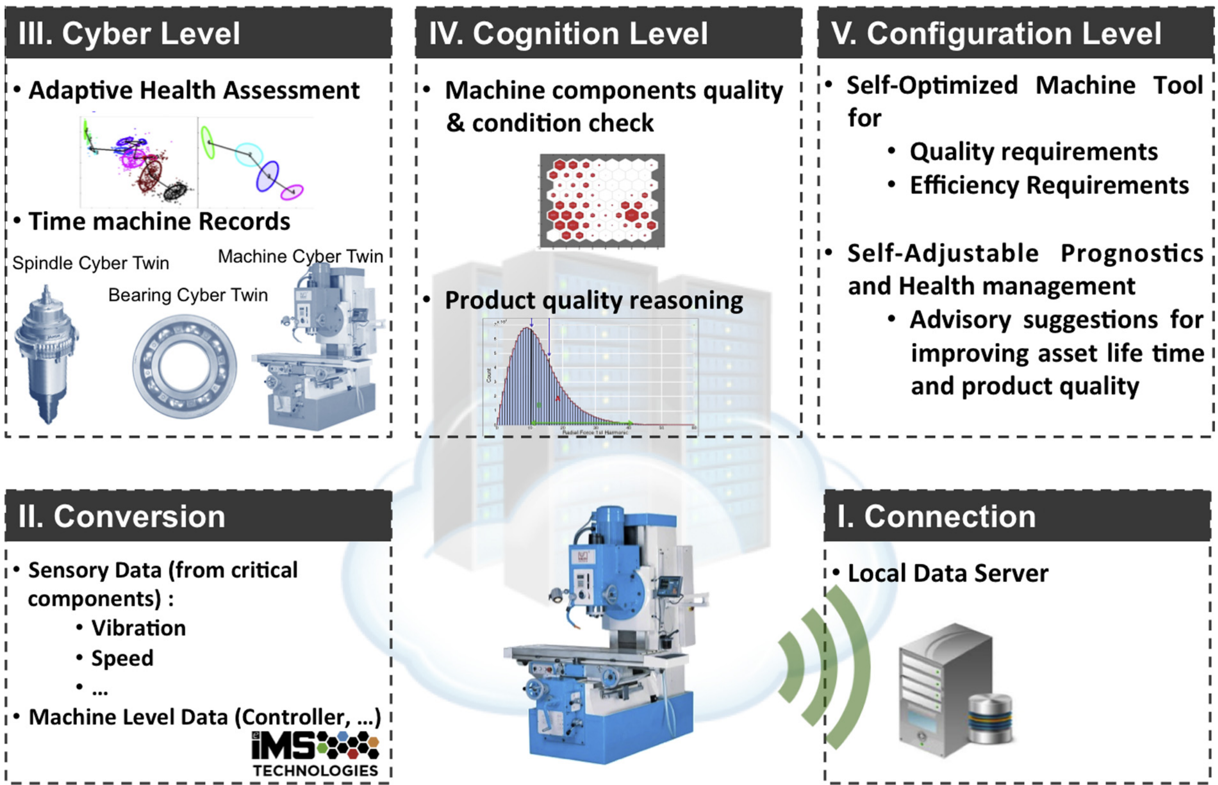

Fig. 4. The flow of data and information in a CPS enabled factory with machine tools in production line based on 5C CPS architecture.

utilization efficiency based on its current health status. Historical utilization patterns of similar asset at various health stages provide required information to simulate possible future utilization scenarios and their outcome for the target asset. Among those scenarios, the most efficient and yet productive utilization pattern can be implemented for the target asset.

4. Implementation of 5C CPS architecture for factories

Implementing CPS in today's factories offers several advantages that can be categorized in three stages of component, machine and production system that have been introduced in Table 1. Considering a production line consists of a numerous amount of machine tools, the advantages of a CPS enabled company at the aforementioned stages can be observed. At the component stage, once the sensory data from critical components has been converted into information, a cyber-twin of each component will be responsible for capturing time machine records and synthesizing future steps to provide self-awareness and self-prediction. At the next stage, more advanced machine data, e.g. controller parameters, would be aggregated to the components information to monitor the status and generate the cyber-twin of each particular machine. These machine twins in CPS provide the additional self-comparison capability. Further at the third stage (production system), aggregated knowledge from components and machine level information provides self-configurability and self-maintainability to the factory. This level of knowledge not only guarantees a worry free and near zero downtime production, but also provides optimized production planning and inventory management plans for factory management (Fig. 4).

5. Conclusions

This paper presents a 5C architecture for Cyber-Physical Systems in Industry 4.0 manufacturing systems. It provides a viable and practical guideline for manufacturing industry to implement CPS for better product quality and system reliability with more intelligent and resilient manufacturing equipment.

References

[1] Baheti R, Gill H. Cyber-physical systems. Impact Control Technol 2011:1–6.

[2] Lee J, Lapira E, Bagheri B, Kao H. Recent advances and trends in predictive manufacturing systems in big data environment. Manuf Letter 2013;38:41.

[3] Shi J, Wan J, Yan H, Suo H. A survey of cyber-physical systems. In: International conference on wireless communications and signal processing (WCP), November 2011; p. 1–6.

[4] Krogh BH. Cyber physical systems: the need for new models and design paradigms. Carnegie Mellon University. p. 1–31. <http://www.control.lth.se/user/karlerik/Illinois/Cyber-Physical/CPS_presentation_krogh.ppt/>.

[5] National Institute of Standards and Technology. Workshop report on foundations for innovation in cyber-physical systems, January 2013

<http://www.nist.gov/el/upload/CPS-WorkshopReport-1-30-13-Final.pdf/.

[6] Lee J, Lapira E. Predictive factories: the next transformation. Manuf Leadership J 2013.

[7] Lee J, Lapira E, Yang S, Kao HA. Predictive manufacturing system trends of next generation production systems. In: Proceedings of the 11th IFAC workshop on intelligent manufacturing systems; 2013. p. 150–6.

[8] Heng S. Industry 4.0: Huge potential for value creation waiting to be tapped. Deutsche Bank Research. <https://www.dbresearch.com/servlet/reweb2.ReWEB?document=PROD0000000000335628&rwnode=DBR_INTERNET_EN-PROD$NAVIGATION&rwobj=ReDisplay.Start.class&rwsite=DBR_INTERNET_EN-PROD/>.

[9] Industry 4.0 in Big Data environment. German Harting Magazine 2013;26:8–10.

[10] Vijayaraghavan A, Sobel W, Fox A, Dornfeld D, Warndorf P. Improving machine tool interoperability using standardized interface protocols: MTConnect. In: Proceedings of the 2008 international symposium on flexible automation (ISFA), 2008, Atlanta, GA, USA.

[11] Wang T, Yu J, Siegel D, Lee J. A similarity-based prognostics approach for remaining useful life estimation of engineered systems. In: International conference on prognostics and health management (PHM). IEEE; 2008. p. 1–6.

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Cyber-physical production systems: Roots, expectations and R&D challenges

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Abstract

One of the most significant directions in the development of computer science and information and communication technologies is represented by *Cyber-Physical Systems (CPSs)* which are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet. *Cyber-Physical Production Systems (CPPSs)*, relying on the newest and foreseeable further developments of computer science, information and communication technologies on the one hand, and of manufacturing science and technology, on the other, may lead to the 4th Industrial Revolution, frequently noted as *Industry 4.0*. The key-note will underline that there are significant roots generally – and particularly in the CIRP community – which point towards CPPSs. Expectations and the related new R&D challenges will be outlined.

Selection and peer-review under responsibility of the International Scientific Committee of “The 47th CIRP Conference on Manufacturing Systems” in the person of the Conference Chair Professor Hoda ElMaraghy”

Keywords: Manufacturing systems, cyber-physical systems, distributed systems

1. Introduction

Cyber-Physical Systems (*CPS*) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet [1], [2], [3]. “The potential of CPS to change every aspect of life is enormous. Concepts such as autonomous cars, robotic surgery, intelligent buildings, smart electric grid, smart manufacturing, and implanted medical devises are just some of the practical examples that have already emerged [3].”

Cyber-Physical Production Systems (*CPPS*), relying on the newest and foreseeable further developments of computer science (CS), information and communication technologies (ITC), and manufacturing science and technology (MST) may lead to the 4th Industrial Revolution, frequently noted as Industry 4.0 [4]. According to the Federal Ministry of Education and Research, Germany (BMBF): “Industry is on the threshold of the fourth industrial revolution. Driven by the Internet, the real and virtual worlds are growing closer and closer together to form the Internet of Things. Industrial production of the future will be characterized by the strong individualization of products under the conditions of highly flexible (large series) production, the extensive integration of customers and business partners in business and value-added processes, and the linking of production and high-quality services leading to so-called hybrid products [4]”.

In this paper, the parallel development of CS and ICT on one hand, and of manufacturing on the other, is described, pointing out the convergence of the two worlds, namely the virtual and physical ones. The concept of cyber-physical production systems is introduced in short, together with the high expectations towards them. The roots of CPPSs are also enumerated, and the main research challenges towards the realization of CPPS are highlighted.

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2. Interplay between CS, ICT and manufacturing automation

If we look through the development of computer science (CS), information and communication technologies (ICT) and manufacturing automation, a parallel development can be observed (Fig. 1). The development of computers led to the numerical control of machine tools and robots, the microprocessor were the heart of computer numerical control (CNC), the application of computer graphics resulted in computer-aided design (CAD) systems. The development of manufacturing systems was unimaginable without computer networks. The data of computer-integrated manufacturing (CIM) systems were stored in databases. The newest results of artificial intelligence (AI) and machine learning significantly contributed to the intelligent manufacturing systems (IMS). Computer vision algorithms were applied in robotics for recognizing the environment and the object to grasp. The internet revolutionized the cooperation of humans and systems (extended enterprises (EE), supply chain management (SCM) or production networks (PN)). Multi-agent systems were applied for realizing agent-based manufacturing and holonic manufacturing systems (HMS). Wireless communication, sensor networks and internet of things (IOT) made the development of high resolution manufacturing systems possible [5], and tracking and tracing solutions in production. Embedded systems helped in realizing product-service systems, while the semantic web solutions supported the interoperability of systems by using ontologies. Grid computing led to grid manufacturing, and similarly, cloud computing to cloud services to manufacturing.

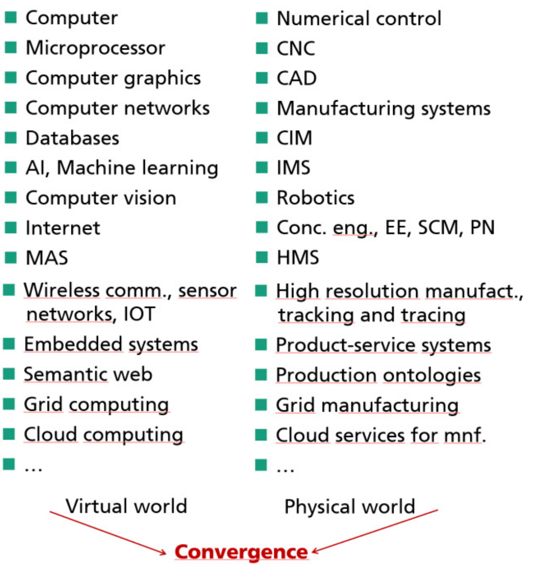

Fig. 1. Interplay between CS, ICT and manufacturing.

Summarizing, the results of CS and ICT undoubtedly contributed to the development in production, but this was not a one-way street: the importance and highly complex nature of production gave newer and newer challenges for the representatives of other disciplines.

As we look at this parallel, mutually inspiring development a kind of convergence can be observed, namely between the virtual and physical worlds (Fig. 1).

2.1. Cyber-physical production systems (CPPS)

CPPS consist of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks. Modelling their operation and also forecasting their emergent behavior raise a series of basic and application-oriented research tasks, not to mention the control of any level of these systems. The fundamental question is to explore the relations of autonomy, cooperation, optimization and responsiveness. Integration of analytical and simulation-based approaches can be projected to become more significant than ever. One must face the challenges of operating sensor networks, handling big bulks of data, as well as the questions of information retrieval, representation, and interpretation, with special emphasis on security aspects. Novel modes of man-machine communication are to be realized in the course of establishing CPPS.

CPPS partly break with the traditional automation pyramid (left side of Fig. 2). The typical control and field levels still exist which includes common PLCs close to the technical processes to be able to provide the highest performance for critical control loops, while in the other, higher levels of the hierarchy a more decentralized way of functioning is characteristic in CPPS.

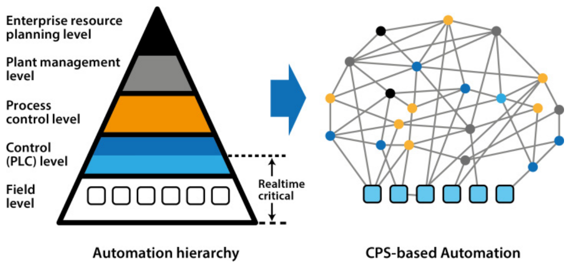

Fig. 2. Decomposition of the automation hierarchy with distributed services [6].

CPPS will enable and support the communication between humans, machines and products alike. The elements of a CPPS are able to acquisition and process data, and can self-control certain tasks and interact with humans via interfaces (Fig. 3).

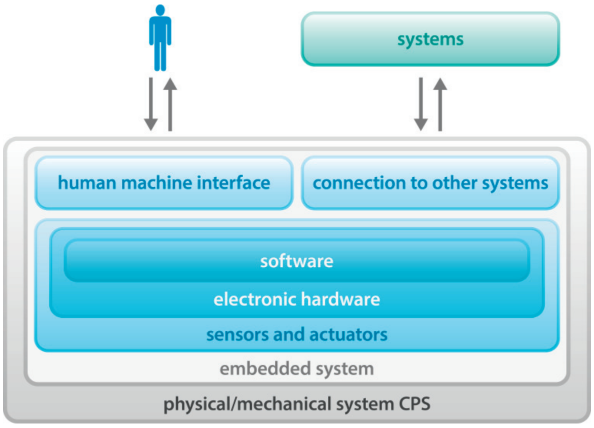

Fig. 3. Interaction between humans and machines in cyber-physical systems [7].

3. Expectations towards CPS and CPPS

Expectations are manifolds, sometimes over exaggerated:

- robustness at every level,
- self-organization, self-maintenance, self-repair, generally, self-X,
- safety,
- remote diagnosis,
- real-time control,
- autonomous navigation,
- transparency,
- predictability,
- efficiency
- model correctness, etc.

Through CPS, the development of new business models, new services are expected which may change many aspects of our life. The potential application fields are almost endless: air- and ground-traffic; discrete and continuous production systems; logistics; medical science, energy production, infrastructure surrounding us, entertainment, and we could keep on enumerating. Through cyber-physical approaches, they could result in smart cities, production-, communication-, logistic- and energy systems; furthermore, they could contribute to creating new quality of life. In the latter case we may either talk about cyber-physical society, which already includes human, social, cultural spheres as well, above the physical- and cyber spaces.

As to CPPS, many see the opportunity for the fourth industrial revolution in it (Fig. 4). The first industrial revolution is contributed to the first mechanical loom, from 1764, the second to the Ford assembly belt from 1913, the third to the first PLC in 1968. It is envisioned that CPPS can bring a similar big jump as the above mentioned breakthrough inventions.

4. Roots of CPPS in manufacturing

As in the case of many revolutions, there are some significant previous phenomena which in a way ring in the big changes. In the coming space, some former developments in production will be enumerated, with special emphasis on the reported results within the International Academy for Production Engineering CIRP, which can be considered as roots of CPPSs.

- Intelligent manufacturing systems (IMS) which were expected to solve, within certain limits, unprecedented, unforeseen problems on the basis even of incomplete and imprecise information [8], [9]. Artificial intelligence and machine learning methods play a significant role here [10], [11].
- Biological manufacturing systems (BMS) which are based

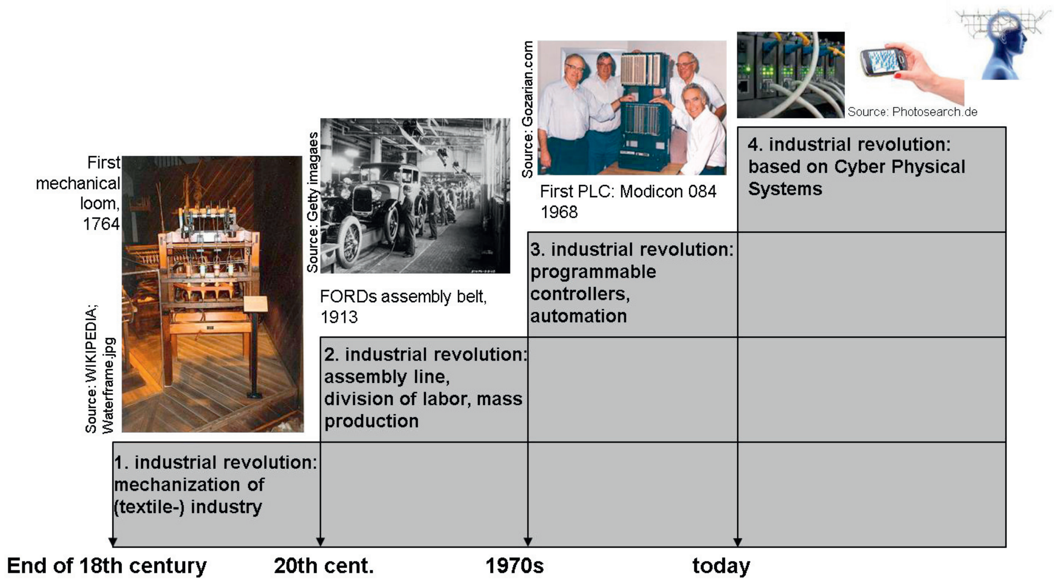

Fig. 4. CPPS as the fourth industrial revolution (after [4], courtesy of O.Sauer)

on biologically inspired ideas such as self-growth, self-organization, adaptation and evolution [12].

- Reconfigurable manufacturing systems (RMS), where the components are reconfigurable machines and reconfigurable controllers [13].
- Digital factories (DF), the mapping of most of the technical and business processes into the digital world [14], [15], [16].
- Holonic manufacturing systems (HMS), agent-based manufacturing, where the two main characteristics of the entities are autonomy and cooperation [17], [18], [19], [20], [21].
- Emergent synthesis methodologies [22].
- Production networks [23].
- Changeable production structures [24].
- Cooperative, responsive manufacturing enterprises [25].
- Co-evolution of products, processes and production systems [26][26].
- Complexity handling in engineering and manufacturing [26].

All of these cornerstones address at least one but mostly several issues which are highly related to the R&D challenges raised by CPPSs.

5. R&D challenges

The expectations towards CPS and CPPS are versatile and enormous: robustness, autonomy, self-organization, self-maintenance, self-repair, transparency, predictability, efficiency, interoperability, global tracking and tracing, only to name a few. Though there are very important developments in cooperative control, multi-agent systems (MAS), complex adaptive systems (CAS), emergent systems, sensor networks, data mining, etc., even a partial fulfilment of these expectations would represent real challenges for the research community.

In the coming space only some of the R&D challenges are outlined from the much bigger set of research fields which are related to CPPS:

- *Context-adaptive and (at least partially) autonomous systems*. Methods for comprehensive, continuous context awareness, for recognition, analysis and interpretation of plans and intentions of objects, systems and participating users, for model creation for application field and domain and for self-awareness in terms of knowledge about own situation, status and options for action are to be developed.
- *Cooperative production systems*. New theoretical results are to be achieved and the development of efficient algorithms for consensus seeking, cooperative learning and distributed detection is required.
- *Identification and prediction of dynamical systems*. The extension of the available identification and prediction methods is required, as well as, development of new ones which can be applied under mild assumptions on the dynamical system, as well as, the disturbance process.
- *Robust scheduling*. New results are to be achieved in handling production disturbances in the course of schedule execution.
- *Fusion of real and virtual systems*. The development of new structures and methods are required which support the fusion of the virtual and real sub-systems in order to reach an intelligent production system which is robust in a changing, uncertain environment. Novel reference architectures and models of integrated virtual and real production subsystems; the synchronization of the virtual and real modules of production systems and their role-specific interaction; and context-adaptive, resource efficient shop floor control algorithms are needed.
- *Human-machine (including human-robot) symbiosis*. The development of a geometric data framework to fusion assembly features and sensor measurements and fast search algorithms to adapt and compensate dynamic changes in the real environment is required.

6. Conclusions

In this paper the parallel development of computer science and information and communication technologies on one hand, and of manufacturing on the other, was highlighted, pointing out their mutual influence. The concept of cyber-physical production systems was introduced in short, together with the high expectations towards them. The roots of CPPSs were also enumerated, mainly based on contributions by members of the International Academy for Production Engineering (CIRP). Some of the numerous R&D challenges in realizing CPPS were also highlighted. As to more concrete and recent developments, we refer to the literature [28]-[44].

Without any questions, CPPS can be considered as an important step in the development of manufacturing systems. Whether this step would be regarded as the fourth industrial revolution will be decided by the coming generations, but certainly, this will happen with no zero probability.

Acknowledgements

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References

[1] N.N. Cyber-Physical Systems: Driving force for innovation in mobility, health, energy and production. acatech Position Paper, December 2011: 48.

[2] N.N. Integrierte Forschungsagenda Cyber-Physical Sytems. acatech Studie, March 2012: 297.

[3] N.N. Strategic R&D opportunities for 21st century, Cyber-physical systems, Connecting computer and information systems with the physical world. Report of the Steering Committee for Foundations and Innovation for Cyber-Physical Systems, USA, January, 2013: 24.

[4] N.N. Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final report of the Industrie 4.0 Working Group, acatech, April 2013: 78.

[5] Schuh G., Gottschalk S., Höhne T. High resolution production management, CIRP Annals – Manufacturing Technology 2007; 56/1: 439–442.

[6] VDI/VDE-Gesellschaft Mess und Automatisierungstechnik (GMA). Cyber-physical systems: Chancen und nutzen aus sicht der Automation, Thesen und Handlungsfelder, April 2013: 9.

[7] Brettel M., Friederichsen N., Keller M., Rosenberg N. How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. International Journal of Science, Engineering and Technology 2014; 8/1: 37-44.

[8] Hatvany J., The efficient use of deficient information, CIRP Annals – Manufacturing Technology 2013, 32/1: 423-425.

[9] Hatvany J. Intelligence and cooperation in heterarchic manufacturing systems. Robotics and Computer-Integrated Manufacturing 1985 2/2: 101-104.

[10] Monostori L. A step towards intelligent manufacturing: Modeling and monitoring of manufacturing processes through artificial neural networks. CIRP Annals – Manufacturing Technology 1993; 42/1: 485-488.

[11] Monostori L., Márkus A., Van Brussel H., Westkämper E. Machine learning approaches to manufacturing. CIRP Annals – Manufacturing Technology 1996; 45/2: 675-712.

[12] Ueda K., Vaario J., Ohkura KH. Modelling of biological manufacturing systems for dynamic reconfiguration. CIRP Annals – Manufacturing Technology 1997; 46/1: 343–346.

[13] Koren Y., Heisel Z., Jovane F., Moriwaki M., Pritschow G., Ulsoy G., Van Brussel H. Reconfigurable manufacturing systems. *CIRP Annals – Manufacturing Technology* 1999; 48/2: 527–540.

[14] Maropoulos PG. Digital Enterprise Technology—Defining perspectives and research priorities. Proc. of the 1st CIRP Seminar on Digital Enterprise Technology, Durham, UK, 2002; Part V: 3–12.

[15] Kádár B., Lengyel A., Monostori L., Suginishi Y., Pfeiffer A., Nonaka Y. Enhanced control of complex production structures by tight coupling of the digital and the physical worlds. CIRP Annals – Manufacturing Technology 2010; 59/1: 437-440.

[16] Kádár B., Terkaj W., Sacco M. Semantic Virtual Factory supporting interoperable modelling and evaluation of production systems. CIRP Annals – Manufacturing Technology 2013; 52/1: 443-446.

[17] Van Brussel H., Wyns J., Valckenaers P., Bongaerts L., Peeters P. Reference architecture for holonic manufacturing systems: PROSA. Computers in Industry 1998; 37:255–274.

[18] Bongaerts L., Monostori L., McFarlane D., Kádár B. Hierarchy in distributed shop floor control. Computers in Industry 2000; 43/2: 123–137.

[19] Valckenaers P., Van Brussel H. Holonic manufacturing execution systems. CIRP Annals – Manufacturing Technology 2005; 54/1: 427-432.

[20] Monostori L., Váncza J., Kumara SRT. Agent-based systems for manufacturing. CIRP Annals – Manufacturing Technology 2006;55/2: 697-720.

[21] Monostori L., Ueda K. Design of complex adaptive systems: Introduction. Advanced Engineering Informatics 2006; 20/3: 223-225.

[22] Ueda K., Márkus A., Monostori L., Kals HJJ., Arai T. Emergent synthesis methodologies for manufacturing. CIRP Annals – Manufacturing Technology 2001; 50/2: 535-551.

[23] Wiendahl HP., Lutz S. Production in networks. CIRP Annals – Manufacturing Technology 2002; 51/2: 573–586.

[24] Wiendahl HP., ElMaraghy HA., Nyhuis P., Zaeh MF., Wiendahl, HH., Duffie N., Brieke M. Changeable manufacturing - Classification, design and operation. CIRP Annals – Manufacturing Technology 2007; 56/2: 783–809.

[25] Váncza J., Monostori L., Lutters E., Kumara SR., Tseng M., Valckenaers P., Van Brussel H. Cooperative, responsive manufacturing enterprises. CIRP Annals – Manufacturing Technology 2011; 60/2: 797-820.

[26] Tolio T., Ceglarek D., ElMaraghy HA., Fischer A., Hu SJ., Laperrière L., Newman S.T., Váncza J. SPECIES – Co-evolution of products, processes and production systems, CIRP Annals – Manufacturing Technology 2010; 59/2: 672–693.

[27] ElMaraghy W., ElMaraghy H., Tomiyama T., Monostori L. Complexity in engineering design and manufacturing, CIRP Annals – Manufacturing Technology 2012; 61/2: 793-814.

[28] Monostori L., Csáji, BCs. Stochastic dynamic production control by neurodynamic programming. CIRP Annals – Manufacturing Technology 2006; 55/1: 473–478.

[29] Schuh G. Sm@rt logistics: Intelligent networked systems, CIRP Annals – Manufacturing Technology 2006; 55/1: 505–508.

[30] Zühlke D. SmartFactory – Towards a Factory-of-Things, Annual Reviews in Control 2010; 34: 129–138.

[31] Frazzon EM., Hartmann, J., Makuschewitz, T., Scholz-Reiter B. Towards socio-cyber-physical systems in production networks. Procedia CIRP 2013; 7: 49-54.

[32] Wang L. Cyber manufacturing: Research and applications. Proceedings of the Tenth International Symposium on Tools and Methods of Competitive Engineering, TMCE 2014, May 19-23, 2014, Budapest, Hungary: 10 (in print)

[33] Rajkumar R., Lee I., Sha L., Stankovic J. Cyber-physical systems: The next computing revolution. Proceedings of the Design Automation Conference 2011, June 13-18, 2010, Anheim, CA, US: 731-736.

[34] Zühlke D., Ollinger L. Agile automation systems based on cyber-physical systems and service-oriented architectures, Advances in Automation and Robotics, Lecture Notes in Electrical Engineering 2012; 122/1: 567-574.

[35] Kim KD., Kumar PR. Cyber physical systems: A perspective at the centennial. Proceedings of IEEE 2012; 100: 1287-1308.

[36] Ferrari F., Zimmerling M., Mottola L., Thiele L. Virtual synchrony guarantees for cyber-physical systems. Proceedings of the 32nd IEEE International Symposium on Reliable Distributed Systems (SRDS) September 30 – October 3, 2013: 11.

[37] Canedo A., Schwarzenbach E., Faruque MAA. Context-sensitive synthesis of executable functional models of cyber-physical systems. Proceedings of the 2013 ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS), April 8-11, 2013, Philadelphia, PA, US: 99-108.

[38] Spath D., Gerlach S., Hämmerle M., Schlund S., Strölin T. Cyber-physical system for self-organised and flexible labour utilisation. Proceedings of the 22nd International Conference on Production Research, ICPR 22, July 28 – August 1, 2013, Iguassu Falls, Brazil: 6.

[39] Yu X., Cecati C., Dillon T., Simoes, MG. The new frontier of smart grids – An industrial electronics perspective. IEEE Industrial Electronics Magazine September 2011: 49-63.

[40] Gupta A., Kumar M., Hansel S., Saini AK. Future of all technologies – The cloud and cyber physical systems. International Journal of Enhanced Research in Science, Technology and Engineering 2013; 2/2: 1-6.

[41] Schuh G., Potente T., Wesch-Potente C., Hauptvogel A. Sustainable increase of overhead productivity due to cyber-physical-systems. Proceedings of the 11th Global Conference on Sustainable Manufacturing, September 23-25, 2013, Berlin, Germany: 332-335.

[42] N.N. Foundations for innovation: Strategic R&D opportunities for 21st century cyber-physical systems: Connecting computer and information systems with the physical world. Report of the Steering Committee for Foundations in Innovation for cyber-physical systems January 2013; NIST, US: 28.

[43] Spath D., Ganschar O., Gerlach S., Hämmerle M., Krause T., Schlund S. Produktionsarbeit der Zukunft – Industrie 4.0 2013; Fraunhofer Verlag: 150.

[44] Givehchi O., Jasperneite J. Industrial automation services as part of the Cloud: First experiences. Proceedings of the Jahreskolloquium Kommunikation in der Automation – KommA, Magdeburg, November 13-14, 2013, Magdeburg, Germany: 10.