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Cyber-physical systems in manufacturing

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ABSTRACT

One of the most significant advances in the development of computer science, information and communication technologies is represented by the cyber-physical systems (CPS). They 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 (CPPS), relying on the latest, and the foreseeable further developments of computer science, information and communication technologies on one hand, and of manufacturing science and technology, on the other, may lead to the 4th industrial revolution, frequently noted as Industrie 4.0. The paper underlines that there are significant roots in general – and in particular to the CIRP community – which point towards CPPS. Expectations towards research in and implementation of CPS and CPPS are outlined and some case studies are introduced. Related new R&D challenges are highlighted.

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 [2,3,114]. In other words, CPS can be generally characterized as “physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core” [136]. The interaction between the physical and the cyber elements is of key importance: “CPS is about the intersection, not the union, of the physical and the cyber. It is not sufficient to separately understand the physical components and the computational components. We must understand their interaction” [85].

“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 devices are just some of the practical examples that have already emerged [114].”

Cyber-physical production systems (CPPS), relying on the latest and foreseeable further developments of computer science (CS), information and communication technologies (ICT), and manufacturing science and technology (MST) may lead to the 4th industrial revolution, frequently noted as Industrie 4.0 [71].

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 [71].”

In this paper, the parallel developments of CS and ICT on one hand, and of MST on the other, are described, pointing out the convergence of the two worlds, namely the virtual and physical

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ones in the field of manufacturing. The concepts of CPS and CPPS are introduced together with the high expectations of the technology. The roots of CPPS from the viewpoint of MST are enumerated, case studies are introduced, and the main research challenges are also highlighted.

1.1. Summary of a survey on literature

In order to understand the impact of cyber-physical systems and their relation to the manufacturing field the applications, problems, and techniques related to CPS and manufacturing were studied by analysing author provided keywords, using text mining. The objectives of this investigation were twofold: (1) to identify potentially impactful articles that are related to CPS and (2) to find out how CPS has evolved with respect to problems, applications and techniques.

The meta-data of the articles considered in the review were downloaded from the Elsevier database via Science Direct and included title, authors, authors provided keywords, citation counts, publication year of the articles and the journals they were published in. The two queries applied included the term "cyber-physical system" and "cyber-physical system AND manufacturing", respectively. Altogether 4236 unique articles were identified from which almost 2000 were published between 2010 and 2015. Even within this period a remarkable growth can be noticed (Fig. 1) and this trend will continue in 2016 and in the upcoming years.

In the analysis both the author provided keywords and CPS related main keywords were considered. The CPS related keywords were keywords in a stemmed-keywords list containing different names of CPS or related concepts based on [120] and Wikipedia. The latter type was based on the abstracts, keywords of articles Wikipedia provides in the references' part. The list contains 25 keywords and 4 classes (CPS, IOT, Sensor Network and Embedded System).

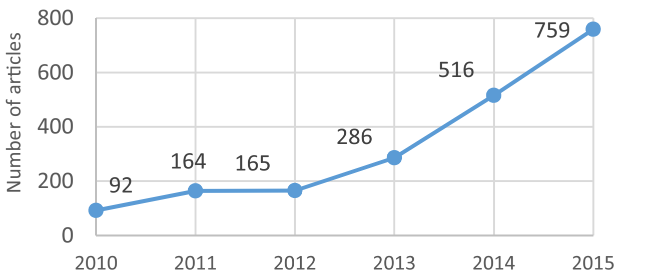

Fig. 1. Number of unique articles per year between 2010 and 2015 in the dataset (1982 articles that were downloaded using the queries "cyber-physical system" and "cyber-physical system and manufacturing").

After normalization of the keywords (e.g. replacing "cyber-physical system" with "CPS", replacing "wireless sensor network" with "Sensor Network", etc.) a tree was created in which the nodes represented the normalized keywords while the edges indicated a co-occurrence of two nodes (keywords). In the initial tree a relative huge number of nodes has been retrieved, therefore, in a post-processing filtering step the number of nodes was reduced to 24 within a tree including 38 edges. The filtered network was obtained by the following processing steps:

1. ranking the sizes of nodes based on their frequency,
2. filtering edges based on 98-percentile of edges-weights, in other words, removing edges if two nodes co-occurred less than 3 times, and
3. removing isolated nodes.

From Fig. 2 one can see that the edge between "IOT" (Internet of Things) and "Security" is the thickest, which might indicate that the security issue is one of the hottest problems of the IOT based approaches. Additionally, the figure shows that multi-agent

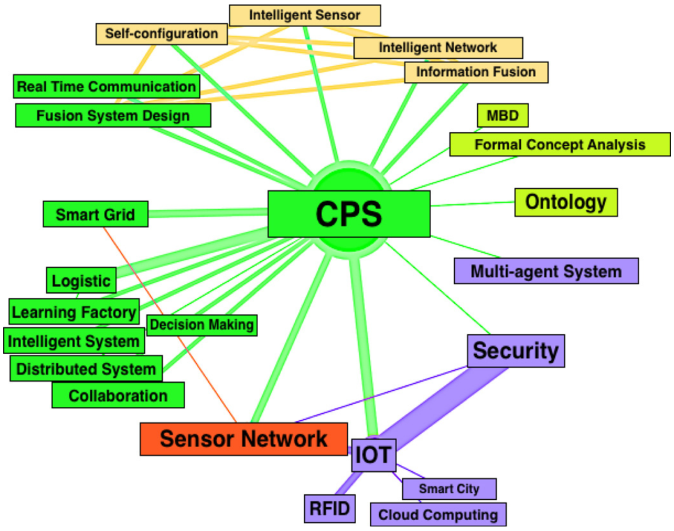

Fig. 2. The network tree with the keywords and their relation after the filtering process.

systems represent one of the most commonly applied techniques related to CPS; RFID and cloud computing are the two most commonly applied techniques in realizing IOT. Moreover, Fig. 2 also indicates that the smart grids, smart cities, logistics are popular areas of CPS implementation.

By looking at 85 percentile of weighted degree of nodes, the analysis also found techniques like simulation and optimization. As to neighbours of "security", it is strongly connected to "privacy", "trust management" and "access control". This provided an insight into security problems related to IOT. By looking at neighbours of "multi-agent system", it can be discovered that it was also strongly connected to "next generation of industrial system". This indicates that as CPS is becoming popular, the use of multi-agent systems might be a good option for manufacturers.

2. Interplay between CS, ICT and manufacturing automation

Looking at the development of computer science, information and communication technologies, and manufacturing science and technology, a parallel development can be observed (Fig. 3).

The development of computers led to the numerical control of machine tools and robots, the microprocessor constituted 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

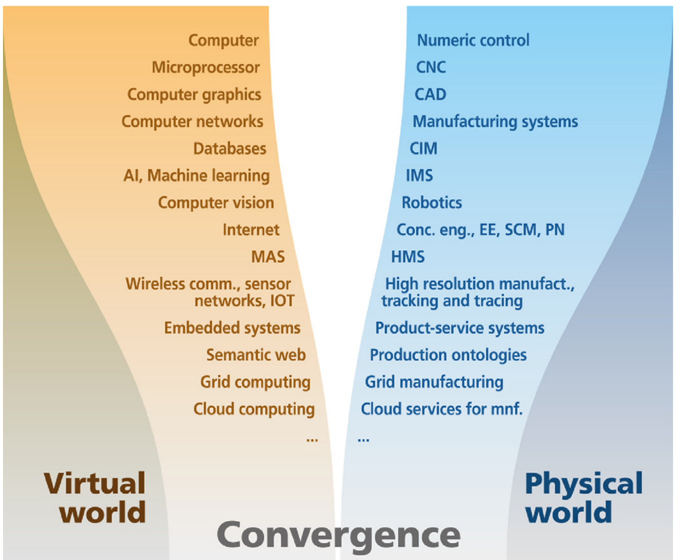

Fig. 3. Interplay between CS, ICT and manufacturing.

computer networks. The data of computer-integrated manufacturing (CIM) systems were stored in databases. The then novel results of artificial intelligence (AI) and machine learning (ML) disciplines 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 humans, humans and systems, and systems and systems, concurrent engineering (CE), extended enterprises (EE), supply chains (SC) or production networks (PN [207]). Multi-agent systems were applied for accomplishing 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 [169], and the tracking and tracing solutions in production [113].

Embedded systems helped in implementing smart automation solutions and product-service systems, while the semantic web solutions supported the interoperability in manufacturing, and similarly, cloud computing the cloud services for manufacturing by using ontologies. Grid computing led to grid manufacturing.

Summarizing all these achievements, the results of CS and ICT undoubtedly contributed to the development in production, but this was not a one-way street: the importance and the highly complex nature of production offered newer and newer challenges for the representatives of other disciplines. Looking at these parallel, mutually inspiring developments, a kind of convergence can be observed, namely between the virtual and physical worlds (Fig. 3).

3. Cyber-physical systems and cyber-physical production systems

3.1. Cyber-physical systems (CPS)

Most of the researchers point to the origins of CPS to embedded systems [125] which are defined as a computer system within some mechanical or electrical system meant to perform dedicated specific functions with real-time computing constraints. These embedded systems are characterized by tight integration and coordination between computation and physical processes. According to this conception, in CPS, various embedded devices are networked to sense, monitor and actuate physical elements in the real world.

The CPS notation can be traced back to 2006, when the first NSF Workshop on cyber-physical systems was held in Austin, Texas, October 16–17. The following announcement can be read on the conference web page: "The research initiative on cyber-physical systems seeks new scientific foundations and technologies to enable the rapid and reliable development and integration of computer- and information-centric physical and engineered systems. The goal of the initiative is to usher in a new generation of engineered systems that are highly dependable, efficiently produced, and capable of advanced performance in information, computation, communication, and control. Sensing and manipulation of the physical world occurs locally, while control and observability are enabled safely, securely, reliably and in real-time across a virtual network. This capability is referred to as Globally Virtual, Locally Physical" [115].

The utmost importance of CPS for US industrial competitiveness was highlighted by the August 2007 Report of the President's Council of Advisors on Science and Technology (PCAST) presenting a formal assessment of the Federal Networking and Information Technology R&D (NITRD). PCAST concluded that the Federal NITRD Program needs to be rebalanced and recommended that the domain of cyber-physical systems be treated as a top priority issue for federal research investments [134]. The National Science Foundation (NSF) put CPS into its highest priorities and regularly initiates research programmes [116].

The following main application fields of CPS were identified by the CPS Vision Statement issued by the federal Networking and Information Technology Research and Development (NITRD) CPS Senior Steering Group [117]:

- agriculture,
- building controls,
- defence,
- energy response,
- energy,
- healthcare,
- manufacturing and industry,
- society, and
- transportation.

In the same mission statement, crosscutting challenges were also outlined that are essential to success in all sectors:

- cybersecurity,
- economics,
- interoperability,
- privacy,
- safety and reliability,
- socio-technical aspects of CPS.

In Germany the National Academy of Science and Engineering (acatech) has been playing and still plays a leading role in promoting CPS [2,3].

CPS maturity model graphically depicted in Fig. 4 originates from Laboratory for Machine Tools and Production Engineering of RWTH Aachen University. The levels of CPS maturity are defined as follows: Setting basics, creating transparency, increasing understanding, improving decision making, and, finally, self-optimizing. While within the first level the organizational and structural conditions for the implementation of CPS are created, the four higher levels represent the maturity of the realizations concerning the information and knowledge processing and the cooperation and collaboration aspects.

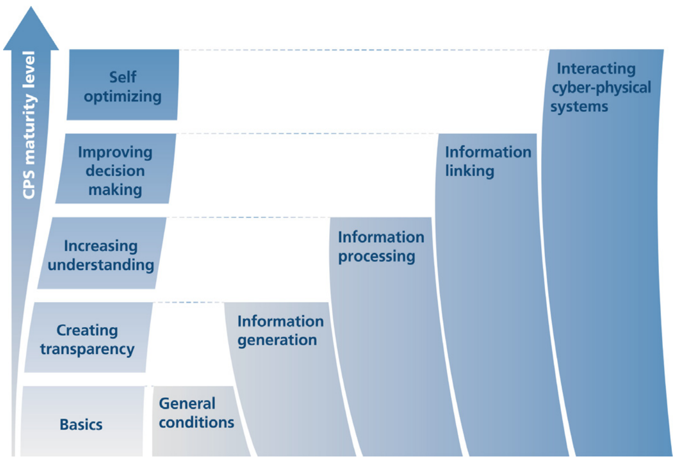

Fig. 4. CPS maturity model.

"Information generation" reflects the need for real-time data availability for all related CPS activities, "Information processing" indicates the existing aggregation instruments in order to deduce new knowledge. On the two highest levels "Information linking" refers to the collaboration-based adaptation of CPS processes while the "Interacting cyber-physical systems" is the most sophisticated layer which can only be achieved by independent problem solving capabilities of collaborative CPS (Fig. 4).

3.2. Cyber-physical production systems (CPPS)

CPPS consist of autonomous and cooperative elements and subsystems that are connected based on the context within and across all levels of production, from processes through machines up to production and logistics networks. Three main characteristics of CPPS are to be underlined here:

- Intelligence (smartness), i.e. the elements are able to acquiring information from their surroundings and act autonomously.
- Connectedness, i.e. the ability to set up and use connections to the other elements of the system – including human beings – for cooperation and collaboration, and to the knowledge and services available on the Internet.
- Responsiveness towards internal and external changes.

Modelling the operation and also forecasting the emergent behaviour of these systems 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 how 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 volumes and rates 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 need to be attained in the course of establishing CPPS.

CPPS partly break with the traditional automation pyramid (left side of Fig. 5). Even before Industrie 4.0, in 2009 Vogel-Heuser et al. described how the automation pyramid, which used to be the 'common sense' for industrial and automation IT architecture, is evolving into a new kind of architecture [198].

Today with CPS we are already more advanced: the typical control and field levels still exist which include common PLCs close to the technical processes in order to be able to provide the highest performance for critical control loops, while at the other, higher levels of the hierarchy a more decentralized way of functioning is characteristic in CPPS (right side of Fig. 5).

The general assumption, i.e. that a CPPS consists of two main functional components, is manifested in the right side of Fig. 5. The lower one is responsible for the advanced connectivity which ensures real-time data acquisition from the physical world and information feedback from the cyber space, while the higher level one incorporates intelligent data management, analytics and computational capabilities that constructs the cyber space.

The 5C architecture introduced in [87] consists of 5 levels in a sequential workflow manner and illustrates how to construct a CPPS from the initial data acquisition through analytics to the final value creation (Fig. 6). On the right hand of the figure some examples are also given from the field of process, machine or system level monitoring. In a CPPS approach the smart connection level (Level I) represents the physical space, Levels II–IV the "pure" cyber space, while the configuration level (Level V) realizes the feedback from the cyber space to the physical space.

The importance of CPPS is hard to underestimate. In the PCAST's Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing of July 2012, 18 recommendations were formulated [135]. In Recommendation No. 2 on

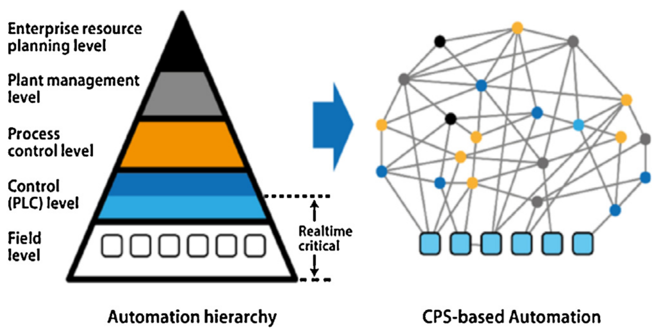

Fig. 5. Decomposition of the automation hierarchy with distributed services [196].

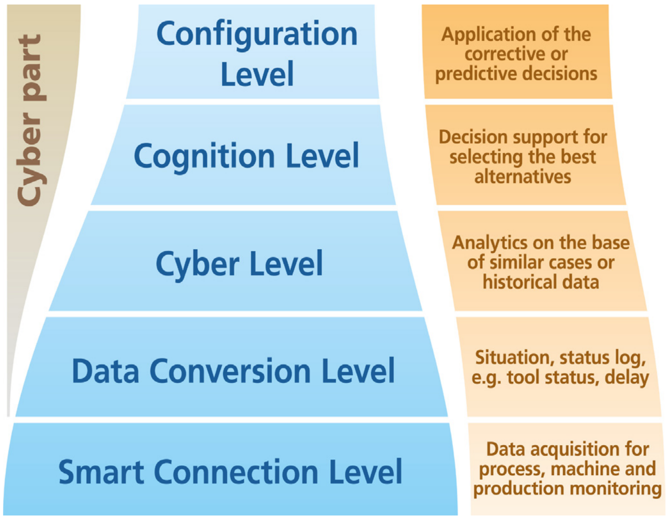

Fig. 6. 5C architecture for implementation of CPPS, after [87].

Increase R&D Funding in Top Cross-Cutting Technologies, the first point was Advanced Sensing, Measurement, and Process Control (Including cyber-physical systems).

In Germany, CPPS play an especially favoured, central role, see e.g. [11,101,158,172,177,215]. The strategic initiative Industrie 4.0 underlines the fact that "Germany has one of the most competitive manufacturing industries in the world and is a global leader in the manufacturing equipment sector" [71]. The implementation of three features of Industrie 4.0 was targeted [71]:

- horizontal integration through value networks,
- end-to-end digital integration of engineering across the entire value chain,
- vertical integration and networked manufacturing systems.

3.3. CPS and CPPS as fundaments for Industrie 4.0

Expectations towards CPS are manifold, sometimes exaggerated:

- robustness at every level,
- self-organization, self-maintenance, self-repair, 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 to emerge 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 one could keep on enumerating. Through cyber-physical approaches, they could result in smart cities, production-, communication-, logistic- [168] and energy systems [212]; smart homes and, furthermore, they could contribute to creating new quality of life. In the latter case one may either talk about *cyber-physical society*, which already includes human, social, cultural spheres as well, above the physical- and cyber spaces [44].

Through CPPS many see the opportunity for the fourth industrial revolution [71]. The first industrial revolution is contributed to the first mechanical loom, from 1764, the second to the Ford assembly line from 1913, the third to the first PLC in

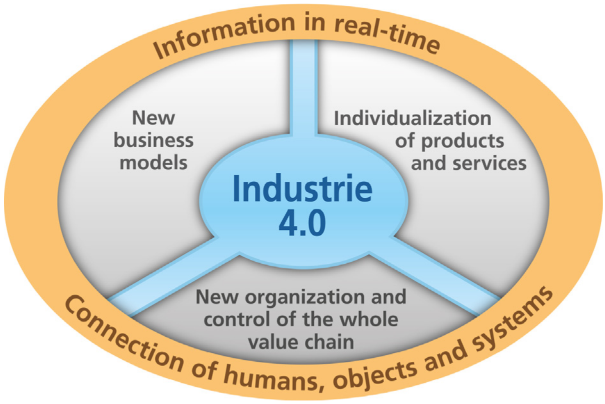

Fig. 7. Industrie 4.0 [10].

1968. It is envisioned that CPPS can bring a similar big jump as the above mentioned breakthrough inventions.

Industrie 4.0 stands for a new way of organization and control of complete value-adding systems (Fig. 7). The key objective is to fulfil individual customer needs at the cost of mass production. Therefore it affects all areas from order management, research and development, manufacturing, commissioning, delivery to the use and the recycling of produced goods. The foundation for the new opportunities is the digitization of production with help of cyber-physical production systems. Therefore all involved resources like workers, products, resources and systems have to be integrated as smart, self-organized, cross-corporate, real-time and autonomously optimized instances [11].

Within global supply networks, machinery, warehousing systems and production facilities will incorporate in the shape of CPPS. These systems will autonomously exchange information, triggering actions and controlling each other independently within a so called Smart Factory [214]. Smart factories allow many potentials: e.g. realization of individual customer requirements, control of dynamic business and engineering processes or an optimized decision-making process. Based on Industrie 4.0 principles, resources' productivity and efficiency can be continuously improved. Finally, Industrie 4.0 enables companies to build up new ways of creating value and novel business models [71].

One current status for CPS in manufacturing is described in the standardization papers of the national Industrie 4.0 platform. It is called "I4.0-component", describing an object plus an administration shell turning it into an intelligent object (Fig. 8).

This description leads to worldwide unique virtual representation for types and instances of objects. These I4.0 components are represented in a reference architecture and communicate with each other by an I4.0 compliant communication. The German standardization process is ongoing; the I4.0-concepts are mapped to existing standards.

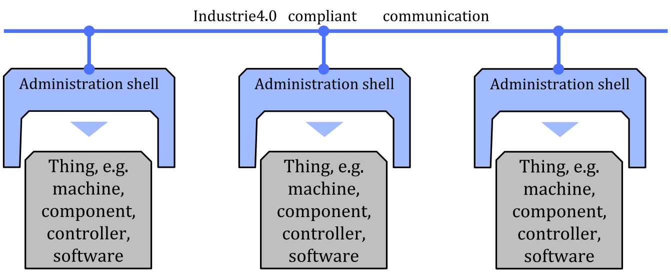

Fig. 8. I4.0 component [197].

4. Roots of CPPS in manufacturing

As in the case of many revolutions, there are some significant preceding phenomena which in a way ring in the big changes [106,105]. In the coming paragraphs, some former developments in production will be enumerated as roots of CPPS, with special emphasis on the results reported within the International Academy for Production Engineering, CIRP.

The term of *Intelligent Manufacturing Systems (IMS)* can be attributed to a tentative forecast of late J. Hatvany and L. Nemes from 1978 [57]. In another landmark paper by J. Hatvany in 1983, IMSs were outlined as the next generation of manufacturing systems that – utilizing the results of artificial intelligence (AI) research – were expected to solve, within certain limits, unprecedented, unforeseen problems on the basis of even incomplete and imprecise information [56]. Machine learning (ML) methods play a significant role here [103,107,110,182]. The application of pattern recognition techniques, expert systems, artificial neural networks, fuzzy systems and hybrid artificial intelligence (AI) techniques in manufacturing was regarded as consecutive elements of a process started in the eighties [104]. In the same paper agent-based (holonic) systems (see later) were highlighted as promising tools for managing complexity, changes and disturbances in production systems. Further integration of approaches was also predicted.

While in the above formulation, the intelligent character of such systems was emphasized, the *World-wide IMS Programme* initiated by H. Yoshikawa in 1992 had a much broader perspective: here the foundation of manufacturing science and technology for the next century through wide range of international cooperation was put as a central paradigm [211].

In order to be able to recognize different situations occurring during the production, sensing, multisensory integration and fusion, and appropriate process, machine, system level *monitoring solutions* are necessary. In this key field including the strongly related mechatronic systems for machine tools, CIRP has a long tradition, and the actual state-of-the-arts and research challenges are regularly presented [24,118,183], and the newest results are reported on [78,21].

The concept of *Biological Manufacturing Systems (BMS)* by K. Ueda aimed at dealing with dynamic changes in external and internal environments in the product life cycle from planning to disposal, based on biologically-inspired ideas such as self-growth, self-organization, adaptation and evolution [187,188]. The papers described models of BMS at a floor level and focused on system reconfiguration. Computer simulation using the principle of self-organization showed that the proposed model indicated adaptive behaviour to the changes in products demands due to external environment and malfunction of manufacturing cells as an internal environment, and it provided the possibility of dynamic reconfiguration of manufacturing systems.

The main benefit of *Reconfigurable Manufacturing Systems (RMS)* by Y. Koren lays in the ability to offer exactly the capacity and functionality needed and exactly when needed [80]. Hence, an RMS can operate both as a dedicated system or as a flexible one or, even as their transitions. Comparing with flexible manufacturing systems, they can more effectively support the introduction of new system elements and the modification of existing ones. Further on, an RMS is able to quickly integrate new technologies and/or functions.

Beyond the obvious economic benefits, taking the recent, urging requirements on environment and health conscious manufacturing into account, reconfigurability can be regarded as a vital feature for production enterprises.

The concept of the *Digital Enterprise* or *Digital Factory*, i.e. mapping most of the technical and business processes into the digital world [69,70,95,205] offers one of the prerequisites for supporting control decisions. However, in order to master the high dynamics in the processes and demand, real-time feedback from the production is required. Having answered these challenges, a tight coupling of the digital and the physical worlds including data mining procedures was described in [69]. Models based on discrete event simulation (DES) of the production can be used in different operation modes (Fig. 9):

- Off-line validation, sensitivity analysis of the schedules against the uncertainties prior to the execution (a).

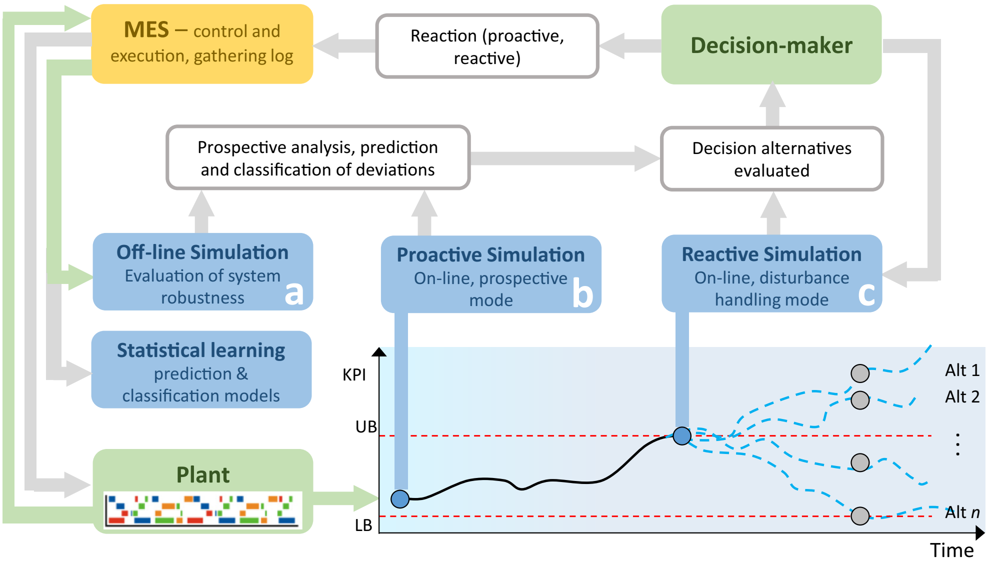

Fig. 9. Plant-level active disturbance handling by using reactive/proactive operation modes of simulation [112,127].

- On-line, anticipatory recognition of deviations from the planned schedule by running the simulation in advance for short-term actions. Support of situation recognition; proactive operation mode (b).
- On-line analysis of the possible actions and minimization of the losses after a disturbance already occurred; reactive operation mode (c).

The *Holonic (or agent-based) manufacturing systems (HMSs)* by H. Van Brussel and P. Valckenaers consist of autonomous, intelligent, flexible, distributed, co-operative agents or holons [18,94,111,192,191,193]. The PROSA reference architecture for HMSs (Fig. 10) identifies three types of basic holons: resource, product, and order holons. Staff holons are also foreseen to assist the basic holons in performing their work. PROSA augmented with coordination and control mechanisms inspired by natural systems (i.e. food foraging behaviour in ant colonies) guarantees that process plans are properly executed under changing conditions, while it continuously forecasts the workload of the manufacturing resources and lead times of the products. The design empowers the product instances to drive their own production; hence coordination can be completely decentralized. In contrast to many decentralized setups, the manufacturing execution system (MES) predicts future behaviour and proactively takes measures to prevent impending problems from happening [191]. Hence, one of the most promising features of HMSs is that they represent a

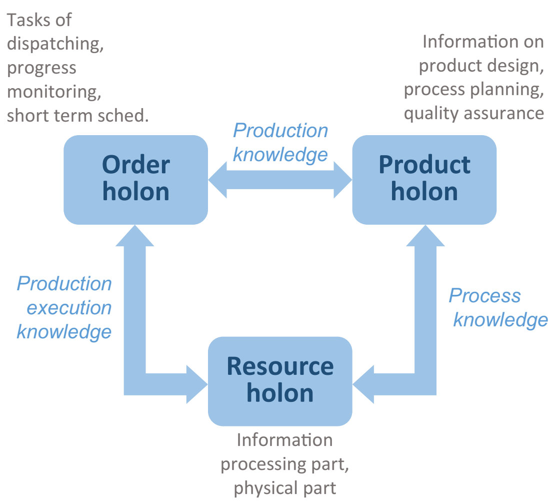

Fig. 10. The PROSA reference architecture [193].

transition between fully hierarchical and heterarchical [55] systems.

Agent-based approaches represent a natural way of realizing CPPS [200].

Autonomous processes in *assembly systems* rely also on agents [53,150,165,159,160,162,163,161,167,164,166,170,173]. Agent-based approaches support the realization of so-called *plug-and-produce (Plug-and-Work) production systems* where various elements are joined to a complete production system without manual configuration efforts [6,38,149]. The main goal of these developments is the creation of a simply manageable agent platform that provides guidelines and facilitates a fast, platform-neutral implementation of the agent technology.

"Gentelligent" components initiated by B. Denkena [30,33] are able to collect information of their lifecycle and to store and communicate them. The term "gentelligent" originates from the words "genetic" and "intelligent", describing components with genetically intelligent properties, as in biology. Genetic information of a component is basic information required to identify or reproduce a component, such as geometrical descriptions or material data. This information is stored in the component as static, unchangeable data and can be inherited from a previous component generation. In addition, the components includes manufacturing data which for example may be enhanced by quality data. The intelligence of a gentelligent component is due to its technical abilities to inherently and autonomously collect data during the utilization phase, such as forces and temperatures, and to process and store them. This is realized by using appropriate materials and sensors, integrated into the component. All data stored in the component can be communicated on demand to the user of the component or readout in case the component is disassembled or replaced. The data as a whole is inherently linked to the gentelligent component and recallable at any time. In this way, a gentelligent component is characterized by inherent sensory properties and the ability to store and communicate component inherent data.

Emergent synthesis methodologies for manufacturing by K. Ueda [186,189]. Environmental conditions are changing, due to agents' interactions as they compete/cooperate for the same resources or for achieving a given goal. This, in turn, changes the behaviour of agents themselves. The most remarkable phenomenon exhibited by the so called *Complex Adaptive Systems (CAS)* [62,63], is the emergence of highly structured collective behaviour over time by the interaction of simple subsystems, usually without any centralized control. The typical characteristics of complex adaptive systems include dynamics involving interrelated spatial and temporal effects, correlations over long length- and time-scales, strongly coupled degrees of freedom and non-interchangeable system elements, to name only the most important ones. Both the CAS and its environment simultaneously co-evolve in order to maintain themselves in a state of quasi-equilibrium, i.e. on the edge of chaos [201].

In designing CAS, non-linear phenomena, incomplete data and knowledge, a combinatorial explosion of states, dynamic changes in environment and the frame problem are some notable examples of difficulties to cope with. The central question is realizing an artefactual system that achieves its purpose in unpredictable conditions [109]. It is difficult to address problems like this by using only existing principles, such as analysis and determinism [179].

Synthesis is a necessary component of problem solving processes in almost all phases of the artifacts' lifecycle that starts with design, goes through the phases of planning, production, consuming and ends up with the disposal of the product. Emergence plays a key role in solving difficult problems arising in synthesis. The main concern here is whether and when, the completeness of information could be achieved in the description of the environment and in the specification of the purpose of the artefactual system. With respect to the incompleteness of information on the environment and/or the specification, the difficulties in synthesis can be categorized into three classes [186,189]:

- *Class I: Problem with complete description*: if all the information concerning the environment and specification are given, then the problem is completely described. However, it is often difficult to find an optimal solution.
- *Class II: Problem with incomplete environment description*: the specification is complete, but the information on the environment is incomplete. Since the problem is not wholly described in this case, it is difficult to cope with the dynamic properties of the unknown environment.
- *Class III: Problem with incomplete specification*: not only the environment description but also the specification is incomplete. Problem solving, therefore, has to start with an ambiguous purpose, and the human interaction becomes significant.

As to CPPS research and their realization one has to face especially with Class II and Class III problems.

Through the concept of *Changeable production structures* by Wiendahl et al. [208], it was recognized that with the increasing global interdependencies of manufacturing firms and market dynamics, the whole factory including assembly, logistics and even the site and buildings have to be considered as well. The word changeability in this field was introduced as an umbrella for the different types of flexibility at various levels and objects of a factory [4].

Co-evolution of products, processes and production systems is an important new paradigm which reflects on the fact that manufacturing products, processes and production systems are being challenged by the frequently changing external drivers, including the introduction of new regulations, new materials, technologies, services and communication methods as well as the increasing pressure on costs and sustainability [184].

A fundamental residue of globalization and market uncertainty is the increasing *complexity* of manufacturing, technological and economic systems. In the era of CPPS, complexity issues will have much larger significance, therefore the topic of complexity handling in engineering and manufacturing [37] will receive much more emphasis, i.e. how to mitigate the negative aspects of complexity while managing its positive ones.

Industrial Product-Service Systems (IPS2) [98], with other words hybrid products [71] consider the dynamic interdependencies of product and services throughout the entire life cycle of the product. Smart products represent by using the armoury of CPS the new generation of intelligent, agile, flexible and networked products [1,102,174,175].

Open-architecture products (OAP) represent a new class of products comprising a fixed platform and modules that can be added and swapped. Customers can adapt OAPs to their needs by integrating modules into the platform. For open products to be realized, new cyber-enabled tools are needed to provide design interfaces, tools and methods to help consumers and manufacturers in dealing with the level of freedom of expression provided by this vision of user participation, while at the same time satisfying quality and product safety constraints [81].

Obviously, *cloud computing* will play a significant role in realizing CPPS [49,52,100,151,152,202]. One of its more promising applications is the cloud-enabled prognosis for manufacturing [47] which can support the timely acquisition, distribution, and utilization of information from machines and processes across spatial boundaries. An appropriate prognosis can improve accuracy and reliability in predicting resource needs and allocation, maintenance scheduling and remaining service life of equipment.

The existence of legacy systems hinders the *stepwise introduction of CPPS solutions* into existing manufacturing systems or, the transformation of a whole traditional system to become Industrie 4.0-ready. Similar problems arose at the appearance of the holonic approach [108]. In [153] a concept based on a communication gateway and an information server is presented how production systems can be included into an Industrie 4.0 environment, even though they did not have Industrie 4.0 interfaces [124] when they had been manufactured.

The current situation in manufacturing was succinctly formulated in the paper by Váncza et al. [194], where the concept of *Cooperative and Responsive Manufacturing Enterprises (CORME)* was introduced. In addition to this analysis the conclusions section of the paper practically forecasts the potentials and challenges of the CPS approach in production:

"Manufacturing cannot be considered in isolation any longer: enterprises have to operate in dense interaction networks both with their kin and their socio-ecological environment. At the same time, enterprises have to continuously consider the split between reality and their reflection on what is going on in the world. In other words, enterprises have to rely on a model of their reality, while simultaneously and unremittingly adjusting that model itself. As the paper discussed, the key challenges are heavy, because they are directly stemming from the generic conflicts between competition and cooperation, local autonomy and global behaviour, design and emergence, planning and reactivity, as well as uncertainty and abundance of information. Based on the survey of various solution proposals, one can conclude that balanced resolutions invariably point towards cooperation and/or responsiveness. It was emphasized – and also illustrated through a series of industrial case studies – that production engineering research has to integrate results of related disciplines as well as a broad range of contemporary information and communication technologies. Conjointly, this enables the adequate facilitation of cooperation and responsiveness that are vital in competitive and sustainable manufacturing."

5. Towards standardized communication within CPPS

For the further discussion of cyber-physical approaches and their application and benefits in different scenarios within production, such as Plug-and-Work concepts [130,156], gathering of real time data for condition monitoring and predictive maintenance, etc., two different types of data have to be distinguished:

- *configuration data* which is generated throughout the engineering to describe the physical part of the component or machine the CPPS is attached to, and
- *runtime data* generated during the operation of the machine or component describing in real time the status of the manufacturing process.

5.1. Engineering and configuration of CPPS

5.1.1. Self description by the integration of AutomationML and OPC UA

AutomationML (Automation Markup Language) is one of the upcoming open standard series (IEC 62714) for the description of production plants and plant components. In the context of Plug-and-Work, AutomationML describes the contents – what is exchanged between the parties and systems involved. It serves to model plants and plant components with their skills, topology, interfaces and relations to others, geometry, kinematics and even logic and behaviour.

OPC UA (OPC Unified Architecture) [91] is a platform-independent standard (IEC 62541) for communication between industrial automation devices and systems. It is a standardized communication middleware for automation systems and serves as a bridge between off-line-based engineering tasks and the runtime communication of the involved physical and logical resources of a CPPS. It defines how information is exchanged between the parties and systems involved and deals with data management and communication management including reliability, security and an information model to include object-oriented descriptions.

A joint working group of the AutomationML e.V. and the OPC Foundation deals with the creation of a companion specification '*AutomationML in OPC UA*' [59]. The usage of both standards in combination and collaboration can create synergy and will lead to a wider acceptance and usability of both standards. The working group applies the engineering format AutomationML to online production data and extends the application domain of OPC UA. Therefore, different use cases made possible by combining both standards have been identified and are currently in work.

One opportunity by combining AutomationML and OPC UA is to communicate and operationalize AutomationML by means of OPC UA. It is possible to simplify the creation of OPC UA information models based on existing AutomationML data. This can be realized by a so called OPC UA companion specification taking advantage of analogies between AutomationML and the OPC UA information model. The companion specification for AutomationML consists of an object model including many specific semantics which can be used online by OPC UA with multiple parties/disciplines/tools involved. This makes an online version of the AutomationML model possible – AutomationML models can be exchanged via OPC UA – and includes OPC UA data management, online communication functionality, multi-user support, access methods, security, etc. This is especially important for re-engineering and maintenance type use cases where the AutomationML model evolves over time. The present AutomationML model can be managed by OPC UA and makes an up-to-date description of the system possible. Further information about a first draft can be found in [59].

Another opportunity is the seamless exchange of OPC UA system configuration within AutomationML models. The manual exchange of OPC UA server configuration data is replaced by a standardized/specified description in AutomationML. Parameters to set up OPC UA communication between engineering and other production-related tools can be exchanged using AutomationML. This creates consistent data, produces less errors and results in an easier and faster configuration of UA servers and clients. OPC UA benefits from the description of complete communication network configuration and structure including communication components of sensors and actuators with respect to communication system parameters, network structure and wiring, quality of service, etc.

The combination of AutomationML as engineering exchange format with OPC UA as communication technology creates new possibilities in the context of CPPS.

5.1.2. Plug-and-Work abilities for cyber physical systems

Objects to change within a manufacturing enterprise can be products, technological or logistical processes, parts of the manufacturing facilities or a company's organization. For this paper it is assumed, that IT systems are also objects to change – they have to be adapted to changes in products and facilities on the shop floor. Today the adaption of IT systems is managed and done manually – therefore an automated way of changing the production's IT-systems is proposed. For this purpose two main ideas are described: reading and interpreting a self-description of production equipment and, the enrichment of these descriptions with data from the "digital factory" bridging the gap between planning and operating IT-systems and thus enabling higher adaptivity of manufacturing systems.

5.1.3. Adaptivity by Plug-and-Work

A basic aspect is the identification of control relevant entities within production systems which can be plugged in/connected to the production system and start operation without change of the control applications in the rest of the production system. This also includes the support for the integration and auto-configuration of physical devices. The most important entities are the product including its manufacturing process, the order representing a customer intention regarding a product and the production resources as well as their components (c.f. reference architecture for holonic manufacturing systems, PROSA [193]). Usually, the investigated approaches stem from the assumption that the adaptation of production systems results from three basic functions.

1. Integration of a new controllable entity in the production system able to provide additional or enhanced functionalities (especially production functions) to the production system.
2. Modification of an existing controllable entity of the production system by updating its set of information enabling the entity to provide additional or enhanced functionalities in the production system.
3. Extraction of existing controllable entities of the production system to disable the provided functionalities in the production system.

With the development of the *Internet of Things and Services (IoT and IoS)* [7,50,51,73,204] as well as with the invention of CPPS [23,199], today new technologies and architecture constructions are available and applicable to the extension of the idea of Plug-and-Work. These technologies and constructions are envisioned to be the foundation of the further development of automation systems heading the fourth industrial revolution [72].

All relevant entities during the development of plants, machines, and components shall be able to properly react to adaptation requests. Currently these requests are executed manually and are thereby error prone and time consuming. Following the ideas of CPPS, in the future the adaptation should be (semi)-automatic and self-controlled by the entity or the production system.

This capability, defined as Plug-and-Work, is envisioned in different publications. Prototypical implementations have been presented [46,64,185]. Following [149], Plug-and-Work is defined as the capability of a production system to automatically identify a new or modified component and to integrate it correctly into the running production process without manual efforts and changes within the design or implementation of the remaining production system.

5.1.4. Plug-and-Work for devices

Plug-and-Work must be addressed for the automatic integration of physical resources, e.g. devices, modules, or subsystems. In order to support Plug-and-Work for such resources within networked control systems, according to [140] the following five steps are required:

1. *Physical connection*: To integrate a new physical resource it has to be physically connected to the given network. This step

includes all measures necessary to prepare the network for the reconfiguration procedure.

2. *Discovery*: After a new resource has been physically connected by the user, a Plug-and-Work server instance has to detect the presence of this device in order to start the automated integration process.
3. *Basic communication*: A Plug-and-Work system has to acquire information (e.g. device description) from the newly connected resource. In order to accomplish the information exchange automatically, a basic communication channel, which does not necessarily need to be real-time capable, has to be established ad-hoc between the Plug-and-Work server and the new resource.
4. *Capability assessment*: The Plug-and-Work server has to assess the identity, functionalities and requirements of the new resource. The required information has to be provided by the resource and can be obtained by the Plug-and-Work server via the basic communication link established in Step3.
5. *Configuration*: The resource information has to be integrated into the existing network configuration to allow, e.g. real-time communication. The information obtained in Step 3 has to be processed in order to extract all elements required for the configuration of the network. After the configuration has been completed, the normal operation of the network, e.g. for real-time exchange can be resumed.

5.2. Real time data from CPPS operation

5.2.1. Data from components

It is necessary to distinguish engineering data such as self-descriptions (see Section 5.1) from run time data such as sensor data, which is collected during the manufacturing process in operation. If possible, during run time the same communication protocol is used as during the engineering phase to transfer the configuration data, e.g. OPC UA to communicate between PLC and Manufacturing Execution System or PROFINET to communicate between components and PLC. The sensor data has to be deterministically exchanged with the controller. Therefore, a real-time communication channel is needed; for the PLUG and WORK-case study this is done by the TPS-1 chip [61], which provides PROFINET-based real-time communication.

5.2.2. Data from PLCs and entire processes – Manufacturing Service Bus

An *Enterprise Service Bus (ESB)* is a software architecture model used for designing and implementing communication between mutually interacting software applications in a *service-oriented architecture (SOA)*. There are differences between the SOA utilized by an enterprise through an ESB, and the SOA utilized by the near real-time manufacturing operations management systems in a plant through a *Manufacturing Service Bus (MSB)*. The manufacturing operations' specific requirements for SOA are called Manufacturing 2.0 which differentiates from the so called Manufacturing 1.0 architectures based on standalone client/server data base applications that attempted to represent business process modelling through point-to-point interfaces and custom data transformation between applications [99].

MSB is required due to high transactions, high parametric data load and near real-time requirements of manufacturing operation. The MSB may be scaled down to a plant or area of plant or across multiple production facilities depending on the transaction/data load and response requirements of the work-flows being supported by the plant and shop-floor level applications. The layers where different functions provided by separate service and the data interface requirements between different layers are defined in the well-known ISA-95 standard. This standard is also considered as a baseline when the service oriented architecture are designed and implemented in manufacturing system domains [190].

The ISA 95 is an international standard for the integration of enterprise and control systems developed by an ISA Committee of volunteer experts [66]. The objectives of ISA-95 are to provide both consistent terminology that is a foundation for supplier and manufacturer communications offering consistent information models as well as consistent operations models. The latter is a foundation for clarifying application functionality and how information is to be used. ISA-95 can be used to determine which information has to be exchanged between systems for sales, finance and logistics and systems for production, maintenance and quality. This information is structured in UML models, which are the basis for the development of standard interfaces between ERP and MES systems. On the base of the reference model for enterprise level, manufacturing level SOA was also proposed in [99] (Fig. 11).

The model provides the detailed elements and relationships of Manufacturing 2.0 SOA that enables manufacturing operations within and across production facilities. Nevertheless, although Fig. 11 positions the MSB above satellite MES-like systems, some new initiatives were taken to apply the MSB on a lower level and connect the hardware level (PLC, NC controllers) to MES and SCADA systems which requires, on the one hand, smart objects on the real shop-floor execution side and, on the other, speedier message transfer from MSB.

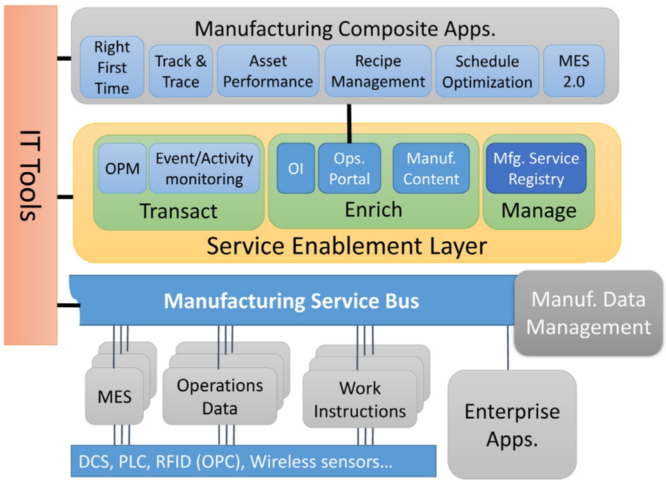

Fig. 11. Manufacturing SOA: Foundation for Manufacturing 2.0 [99].

The first implementations of the MSB-based systems go back to early 2000s [99] and they are still continuing extensively today as new, smarter devices are available on shop floor. Such an initiative is the Virtual Fort Knox project [40], which developed a platform that offers tailor-made functional IT solutions to manufacturing enterprises. The platform simplifies the use of information technology in value-adding processes and optimizes networking beyond geographical and company limits.

Virtual Fort Knox simplifies the use of information technology in value-adding processes and optimizes networking beyond geographical and company limits. In this context the MSB is provided as cloud service which can bridge smart hardware devices and/or services inside factory borders or even connect such entities between different enterprises (Fig. 12).

In the case a SOA architecture is applied, common data format for the exchange of data reduces the number of data transformations necessary as multiple applications communicate with each other.

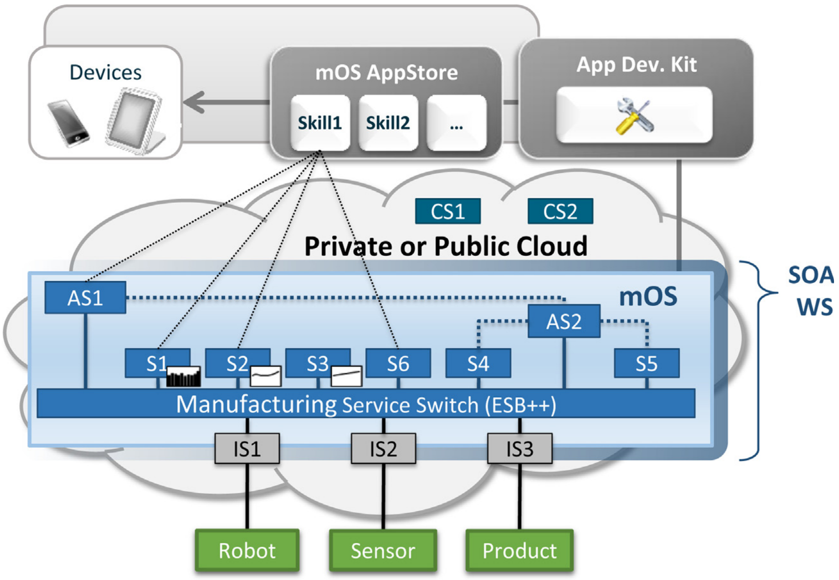

Fig. 12. Architecture of Virtual Fort Knox [10].

6. Case studies

In this Section ten case studies from different application fields are presented in brief spanning over a relatively broad range of application domains from sensor level, through machine and system levels, to the level of supply chains or production networks. Moreover, activities are highlighted aiming at company specific CPPS/Industrie 4.0 strategy development. As to other use cases, reference can be made to the literature [5,9,14,22,36,58,88,119,123,148,171,178,203,210].

6.1. Cyber-physical modules for machine tools

The small and middle batch series production is facing challenges regarding the flexibility during the process of machining. Due to often changing parts during the production process in such companies, the clamping situation can change with every new part. Hence, the productivity of a machine depends strongly on the part itself. Besides the improvement of the machine tools themselves, further central elements of continuous improvement efforts are the tools, clamping equipment or measuring devices of a machine. A possibility to improve the productivity is the equipping of ordinary mechanical elements with electronic components [28,34,142,157].

Within the scope of the research project [13] possibilities for improving the quality and the productivity of the production process by using mechatronic modules are examined.

Generally, two different kinds of mechatronic devices can be distinguished. Passive systems influence the processing of the part indirectly, e.g. 3D scanners that report a contact between part and tool to the machine controls. Active systems influence the process of machining directly by actuators fixed to the tooling. An example for such a system is an actuator tooling that enables multiple different outlines with one clamping.

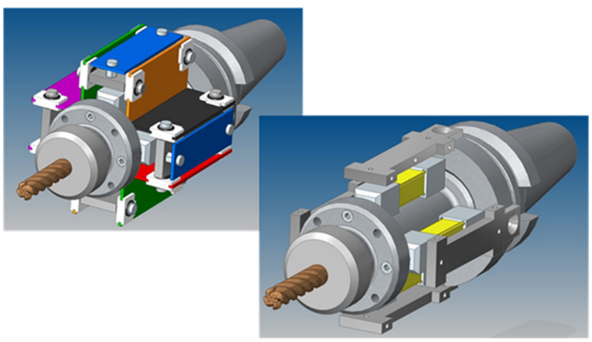

Fig. 13. Tool equipped with sensors for chatter detection.

At the moment, an automatic machine configuration system is being developed. Within that system specific data as ideal machining or tool correction parameters are sent to the machine by the electronic component of the tool before the start of the machining process. This can lead to a reduction of set up times for the machine. Besides the definition of initial values for the machine, a continuous surveillance of relevant parameters during the process is possible. For example, a significant problem is the chattering of the cutting edge during the milling process. Sensors in the tool allow the detection of this phenomenon and thus enable the adaption of relevant process parameters like the tool's feed rate (Fig. 13). Hence, a load dependent adjustment of parameters, e.g. the surface quality of the part can be improved and the life cycle of the tool prolonged. So the combination of mechanical with electronic components increases the profitability of the production process.

Furthermore, it is also possible to equip the clamping device of a process machine with electronic components and thus enable a situational adaption of the clamping parameters to the part. The clamping device can reach a product specific default position based on parameters that are stored on the product and sent via RFID technology to the machine tool. Additionally, it is possible to integrate sensors into the clamping device to facilitate an online surveillance of the relevant parameters. This allows an adaptation of relevant machine parameters and thus the reduction of the processing costs of the product. As to similar approaches reference can be made to the literature [68].

6.2. Plug-and-Work application examples

6.2.1. WISARA lab

One application of the explained requirements, principles and technologies for Plug-and-Work is the WISARA Lab (see Fig. 14). It is a demonstrator for filling liquids.

It includes numerous sensors and actuators especially designed for Manufacturing Execution Systems (MES), e.g. for energy monitoring. The WISARA Lab methods support the test of models, tools and mechanism for adaptability, flexibility and interoperability of production-related IT systems.

In Section 5.1, the requirements for a Plug-and-Work system have been identified which are implemented by the WISARA Lab, e.g. a self-description of each module and the communication ability. In the original demonstrator a gripper module is added to the filling module (module 2) to demonstrate Plug-and-Work abilities (see Fig. 14).

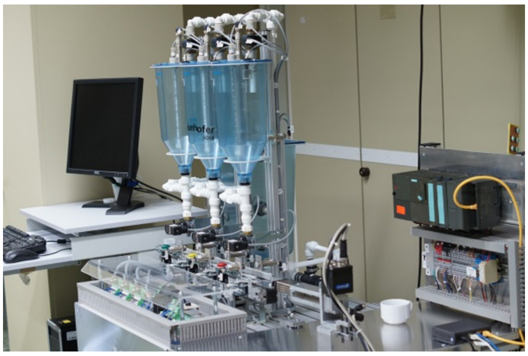

Fig. 14. WISARA Lab with additional gripper module [156].

Both modules (filling and gripper) contain a controller with a communication module including an Ethernet interface. The modules are still controlled by their own controller, but the Ethernet connection combines both modules via a network switch. The resulting visualization for a monitoring and control access changes when the additional gripper module is recognized as OPC UA communication partner after it is plugged in.

6.2.2. Research project SecurePLUGandWORK

Another case for production system components satisfying all the Plug-and-Work requirements mentioned above is developed within the research project SecurePLUGandWORK [43]. It aims at an integrated and secured Plug-and-Work capability on all levels of the automation hierarchy. The goal is to create a more efficient engineering of components and plants to make them more adaptive. The applications and use cases within the project vary from ball screws, spindles, machine tools, tool magazines, gripper systems and industrial cleaning systems to demonstration setups.

Each component involved in the automation system must provide its own description containing aspects such as an object description with attributes and interfaces, the components' production skills, geometry, kinematics, logic and behaviour, and relations to other components, e.g. topology. Automation ML [154] is a suitable technology for resolving this task and can answer the question what to communicate (see also [128]).

According to the requirements, each of the production components as well as the IT systems involved must be equipped with an interface for communicating the contents. This includes the ability to initiate communication as well as data and communication management. This is in line with the definition of an 'Industrie 4.0 component' of the Industrie 4.0 glossary of [42]. There it is defined as a participant of an Industry 4.0 system which is globally uniquely identified, able to communicate in a way conform to I4.0, and offers its services with defined QoS (Quality of Service) properties. The I4.0 component provides task-adequate protection for its services and data. Ref. [195] describes CPS as "Systems which link real (physical) objects with information processing (virtual) objects and processes via open, partly global and permanently linked information networks" [129]. Beside a software realization, the hardware must support Plug-and-Work as well. Different field busses and restrictions of the electrical components in mechanical hardware components must be supported. A SecurePLUGandWORK adapter retrofitting non-communicative plant components helps to reach this goal.

OPC UA is one possible platform-independent standard to solve this problem because it can be used on each level of the automation hierarchy. OPC UA can even be used in combination with IT tools of the production planning phase as described in [155]. The realization may consist of, e.g. an OPC UA server for the controller or a recent integration communication component based on an embedded system. Components which are not able to participate actively in this communication can be supplemented by administration shells in the OPC UA communication infrastructure.

These enablers were considered during the specification of the SecurePLUGandWORK architecture (see Fig. 15). The developed architecture concept comprises different realization levels for all different use cases and applications within the project. They are based on common hardware and software tools and methodologies.

Furthermore, IT security plays a very important role in complex and networked plants. A holistic security concept was integrated by design based on OPC UA. The security server (see Fig. 15) manages in particular all necessary security keys and ensures that they are available on the components, machines or IT systems if necessary.

An 'Industrie 4.0 system' is a "System of I4.0 components which serves a specific purpose, has defined properties and supports standardized services and states" [42]. All SecurePLUGandWORK use case scenarios have more than one Industrie 4.0 component. An I4.0 platform was defined by [42] as an "Implementation of a standardized communication and system infrastructure with necessary management and productive services and defined QoS (Quality of Service) properties as base for an efficient development and integration of Industrie 4.0 systems in an application domain."

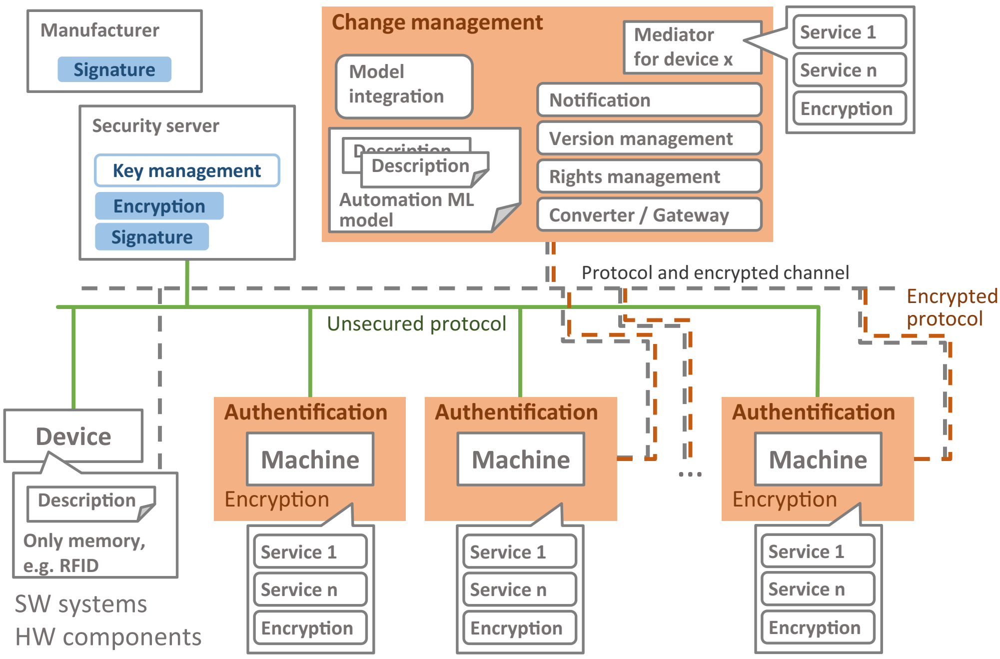

Fig. 15. OPC UA based architecture of SecurePLUGandWORK.

Therefore, the two basic building blocks described (content and communication) are complemented by joint SecurePLUGandWORK components based on both standards. These components accomplish modelling, consistency checks, versioning, role based access control, rights management and notification.

Every participant in SecurePLUGandWORK has a unique identity. Access rights and customization are managed at role level. Roles distinguish between component manufacturers, machine manufacturers, plant manufacturers, service technicians, plant operators or system integrators related to different companies. This makes general components and mechanisms possible, but allows for an individualized behaviour based on the roles.

Every device, component, machine or IT system is equipped with an OPC UA interface, either with an own OPC UA server or via a converter or gateway with a representation in an aggregated OPC UA server. If a standard OPC UA server, e.g. for a controller, is chosen and it does not provide the possibility to secure its communication, a gateway as an aggregated OPC UA server can integrate this server. Legacy OPC servers can be wrapped and integrated via the gateway into the aggregated OPC UA server.

Every device, component, machine or IT system has its own model. This AutomationML model is included in the OPC UA server address space (see [40]), based on a common AutomationML information model.

If the component, machine or IT system is not able to communicate via OPC UA, it is expanded by an additional secure automation device (SecurePLUGandWORK adapter based on an embedded system) which includes the OPC UA server [17].

The SecurePLUGandWORK adapter is based on the BeagleBone Black (BBB) [26] mini PC with sufficient resources to run a complete standard UA Server Profile. Because the system runs on a SD card, plenty of data can be stored persistently. Since the BBB is based on the ARM architecture, it can run Linux as an operating system. Even real-time patches for the kernel are available in order to support time-critical industrial applications.

In order to support security features, the architecture comprises a security dongle [209] which holds the keys and certificates used for the OPC UA communication process. It acts as a key for a device to become part of the plant.

The BBB [26] is used to run an OPC UA server which provides the self-description and configuration data needed at the beginning of operation of the device. Furthermore, it is able to get sensor data and store it. The OPC UA based interface allows the flexibility to connect devices with the joint SecurePLUGandWORK components or any other vendor neutral system, e.g. for diagnosis.

If it is not possible to equip the component with an additional secure automation device, e.g. for cost reasons, it gets an administration shell which takes over the active participation in communication. The AutomationML model can be stored on a physical storage, e.g. RFID, on the component or at the administration shell in the joint SecurePLUGandWORK tools.

6.3. Real system and controller both mapped and synchronized in virtual environment

One of the limiting factors on the widespread and multilevel utilization of digitalization and application of discrete event simulation (DES) technologies is that its efficient application requires not only comprehensive knowledge about the system in consideration, but technology specific knowledge as well. This leads to outsourced simulation studies, where modelling expertise is provided externally. Supplying a proper user interface in the case of third party developed digital models and their daily use are crucial in order to support effective decision making. The parameters of different virtual models, the initial values, the results of experiments all have to be accessed, set, evaluated and displayed in a familiar and understandable way.

Present days' manufacturing systems are tending to be equipped with more and more sensor and data acquisition units and the connectivity and accessibility of these units is improved to new levels by utilizing state-of the art communication networks and technologies. This leads to the prevalence of complex Supervisory Control and Data Acquisition (SCADA) systems. Since SCADA systems are utilized in the daily operation of manufacturing systems, the requirements towards their user interface are very similar to those of a simulation model interface. Adding this fact to the cases when the user of the simulation model is the same person who operates the SCADA system (and the experiments are also in the similar scope) it turns to be a reasonable choice to take the SCADA interface as a basis for the simulation model and its GUI.

In the presented pilot use case implanted in one major automotive player in Hungary the simulation model of a complex conveyor system was developed in a commercial simulation software. Because of the extensive and complex nature of the system in consideration, the resulting simulation model has a large set of parameters and results to return. Providing a proper user interface to these data was carried out by creating a mirrored instance of the SCADA interface which was mapped to the simulation model instead of the real factory (see Fig. 16). Initializing the simulation model is accomplished by using time production data, exported from the real SCADA system, resulting in a simulation model displaying the actual status of the system.

The above feature of the simulation model and the interface similar to the one in the SCADA system allow for executing what-if scenarios and experiments with the same parameters as for the real system and evaluate the results by using the same measures and performance indicators.

Providing a powerful user interface for a simulation model, however, does not solve another crucial issue of simulation modelling, which is the time consuming nature of model building. Flexible daily industrial usage of simulation not only relies on a proper user interface but periodic model updates and efficient model building as well. The presented use case utilizes the technique of automatic model building in order to speed up model building and thus keeping the model efficiently up to date. Control codes extracted from low-level controllers (PLCs) of the manufacturing system were transformed by using a tailored grammar interpreter into a model definition database. This database provides input for methods which build up the simulation model in an automatized way [132].

The use case therefore utilizes data acquired from two different levels of the automation hierarchy. The simulation model is built up automatically from the data stored in low level controllers, while the user interface is defined to mirror the existing SCADA system of the manufacturing system. This offers the advantage of having an efficiently maintainable simulation model controlled by an interface which is user friendly both in its layout and its structure as well, thus supporting everyday usage of simulation modelling in decision support.

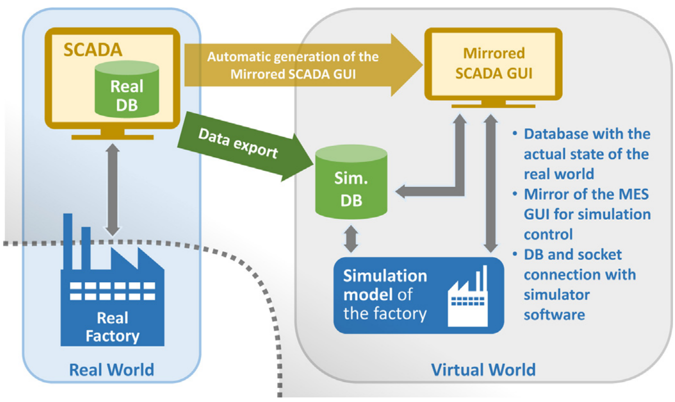

Fig. 16. Real system and controller both mapped and synchronized in virtual environment for decision support and teaching.

6.4. Automated generation of process plans

The necessary efforts for the creation of correct and reliable process plans in individual and small series production are relatively high because they cannot be spread on a large number of units produced [206]. Due to a dynamic manufacturing environment, production processes need to be adapted regularly but these changes are often neglected on the documentation side in order to minimize associated efforts. Therefore, automated planning processes which reduce the manual planning efforts, offer the opportunity to increase planning quality and contribute to a more economic small series production [145]. Overall, the benefits of automated process plan generation are highly evident to manufacturing companies. However, one major challenge is the integration of the employees' expertise into the automated creation of correct and reliable process plans. This integration needs to be efficiently managed without creating elevated individual efforts [31].

At a medium sized producer of drive unit elements, the automated generation of process plans is implemented as a three-step process. In a first step, initial process plans are generated with the help of commercial CAPP (Computer Aided Process Planning) software and then validated, adapted and automatically adjusted by using the first units from pilot production. In a second step, feasible initial machine sequences are validated, while the third step does so for the estimated processing times. The planning of these two steps usually makes up approximately 50% of the planning time [206].

The CAPP software used in the first step relies on a database which contains among other things information on technologies, resources and materials which were used in the past in order to classify newly designed products based on their geometrical features. This information in turn is translated into an initial process plan. Since the classification and process step allocation algorithms used by the CAPP software are based on historical data, process plans generated for novel products often need refinement [145].

In the second step, this refinement is provided regarding the prevailing and other possible machine sequences by automatically analysing the feedback data from the first units produced in pilot production. Order numbers are logged into production data acquisition terminals and can therefore be associated with their actual machine sequences (Fig. 17). In the example, the machine sequence provided by CAPP is followed in 74% of the initially produced units. However, in 26% of the initial orders a total of three alternative machine sequences are chosen by the experienced shop floor personnel. This circumstance is registered by a prototypical software tool which presents the production planner with the option to include the three alternative process plans for the new product in the given example. This represents a change in the mind-set regarding the division of labour, because of the implicit contribution of the shop floor personnel to the generation of the final process plans and therefore, that of the production planning as well.

In the third step, the software tool analyses the feedback data from machine data collection in order to adjust the initial standard processing times provided by CAPP. The feedback data is adjusted first for infeasible data points, like physically impossible processing times close to zero. Subsequently, the data is statistically adjusted by filtering out fringe percentiles, as configured by the user. The residual data points are used to calculate a moving average of the real processing times, which is presented to the production planner as a suggestion to adopt as the standard processing times.

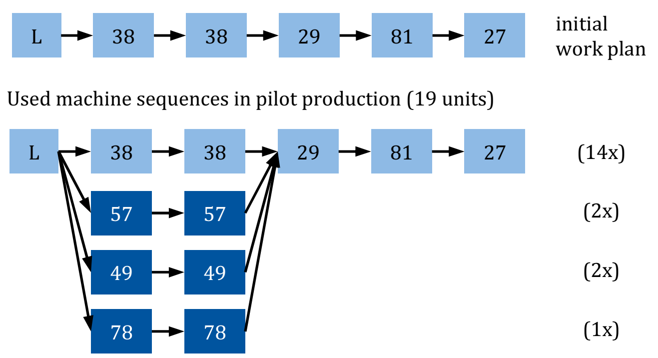

Fig. 17. Intended and real machine sequences.

In an example run with the described methodology, the average processing time deviation from plan was reduced from 15% to 6% by validating and updating the initial standard time during the pilot production run.

Using prevailing commercial CAPP software in combination with feedback data from the first produced units can provide correct and reliable work plans for novel products as shown in the case study. At this point, the software tool provides the production planner with decision support regarding adjustments to the initial process plan but is intended to work fully autonomously in the future.

6.5. Scheduling with alternative routings in CNC workshops

Changes and disturbances may necessitate even the modification of the process plans of the workpieces in an on-line manner. A new approach for the simulation supported planning and monitoring of cutting processes was described in [29,32]. Fig. 18 illustrates the main concept: during detailed planning, a process simulation is used for verifying the generated plans and identifying the thresholds for measurable process parameters (1). The values are integrated into the process plan and transferred to the process monitoring system (2) and serve as basis of early warning of risk situations. Factual experience is fed back into the process simulation and the planning to adjust the process model (3). As a combination of process planning and process control, adaptive process planning allows for a reactive process control [29].

In practice, computer-aided process planning (CAPP) and manufacturing (CAM) generate typically a unique process plan and corresponding NC code for each product which determine a fixed routing along some resources whenever an order is released as a job for production. This process plan is typically the one that is judged the most efficient in the hypothetical situation that no resource conflict arises with other orders. In real production, this is rarely the case.

In [121] a scheduling approach and a scheduling system developed accordingly were introduced which can handle alternative routings. The main goal was to optimize the manufacturing efficiency of factories which operate a number of different types of machines with overlapping capabilities. As a result, on the base of the actual situation on the shop floor, e.g. the types and number of the available machines, adaptive process control can be realized.

As a counterpart of this complex approach, an automated process planner was also developed [122]. Departing from the design models of the parts and the description of the available processes and resources, executable process plan alternatives

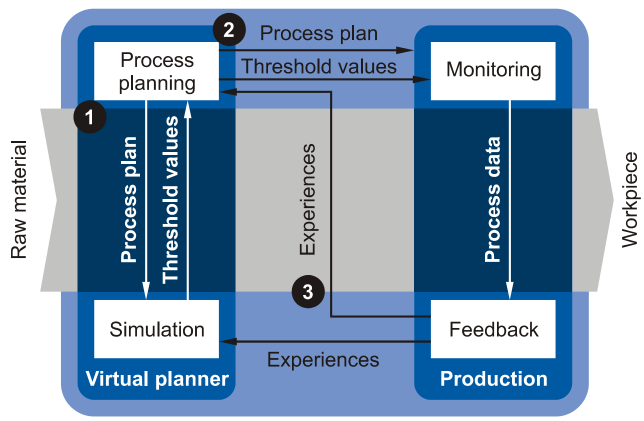

Fig. 18. Planning and machining Gentelligent components [29].

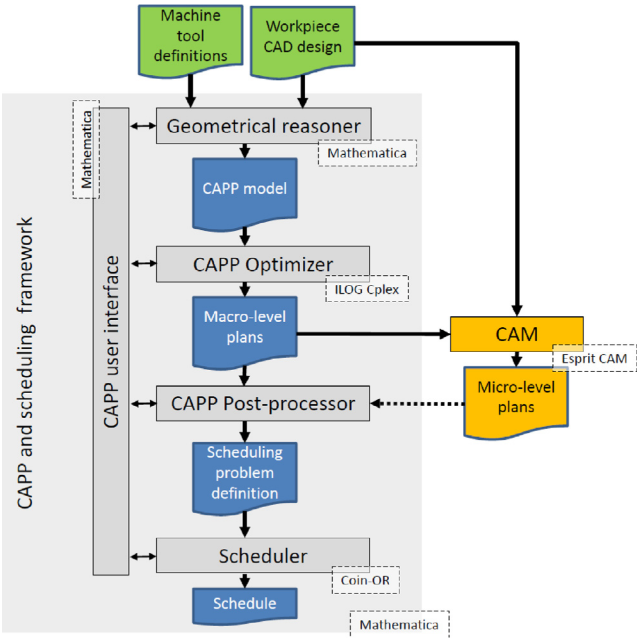

Fig. 19. Architecture of the integrated process planning and scheduling system [122].

optimized according to the usual engineering criteria, e.g., minimal setups and processing times, are generated.

The structure of the integrated process planning and scheduling system is illustrated in Fig. 19.

6.6. Adaptive scheduling through product-specific emergence data

A successful production planning and hence the competitiveness of a company in a globalized market with a high diversity strongly depends on the quality of the data provided for Production Planning and Control (PPC). In many cases existing production plans cannot be kept on the shop floor. One of the reasons for this is that the actual production related data differ from those – usually average values – which were used during the production planning process [138].

These challenges can be met by a methodology for an adaptive scheduling relying on product specific emergence data. The products are equipped with RFID tags which facilitate besides the storage of master data, e.g. order number, on the product, the collection and storage of actual data about the production process. A connection to the production resources of a company is originated by a sensor network, consisting of RFID antennas and -readers, which additionally enables the collection of resource specific data during the production of a single product (Fig. 20).

These product specific emergence data are stored in a database after the termination of the production process. This database is examined with the help of big data techniques regarding discrepancies relevant to the master data. In case of detection of relevant discrepancies, the master data is accordingly adjusted whereupon the discrepancies have to be discerned whether they are dependent or independent upon the particular conditions on the shop floor. The discrepancies caused independently from the actual conditions are causing a universally valid change in the master data.

The differences influenced by the actual conditions lead to an extension of the master data. The extended master data is then only valid for a product when same conditions prevail on the shop floor again. Working plans which provide for alternative resources for a process step of a product or variable process times are a requirement for such an adaptive planning [138].

The eXtensible Markup Language (XML) which stands out because of its high level of adaptability has been used to store the data on the RFID tags. After completion of the production process, the data is read and stored in a database according to a concept

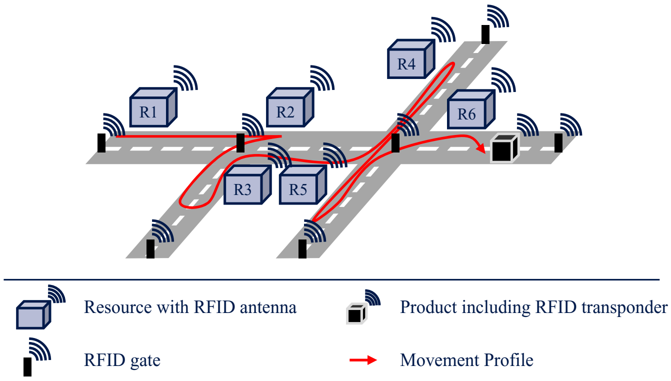

Fig. 20. RFID-based product specific emergence data acquisition [138].

developed to render the data accessible to run analyses [138]. Additionally, a simulation model has been developed to guarantee a sufficiently large number of orders and hence to ensure the validity of the results. The simulation model consists of six workshops each having two to four resources available. It was shown that the adherence to delivery dates could be increased by 19% from 74% to 93% when scheduling with static master data is compared to scheduling with dynamic master data and the use of product specific emergence data. The idle times of machines could also be reduced significantly. Furthermore, the quality of the information used for scheduling could be improved as well. The deviation of the throughput time (TPT) between the production plan and reality could be lessened from 17% to only 2% to 3% for a specific resource [139]

6.7. Cyber-physical support for maintenance strategy

In this example the need for anticipative maintenance strategies based on a combination of various data-sets including historical, real-time, and planning data is addressed.

Due to growing competition and market globalization, product quality and delivery reliability have become central key factors for success in the manufacturing industry. Besides this, the increasing emphasis on sustainable production requires maintaining the resource efficiency and effectiveness along the product, process and production system life cycle [180]. The continued pressure to reduce costs and in parallel, to improve customer satisfaction results in a detailed examination of maintenance strategies. Especially the need of reducing costs and, therefore, minimized machine parks have made production systems increasingly vulnerable to risk as equipment break downs can result in fatal loss of production.

In the context of large-scale production with constant machine loads, conventional maintenance strategies can be applied, whereas in customer order driven lean production processes current approaches of preventive maintenance fail because they are not able to respond to specific load spectrums.

The proposed real case is related to the maintenance of machine tools for manufacturing car engines and gearboxes in the automotive industry. The manufacturer Opel GmbH is located in Vienna, Austria and has been producing car-engines and gearboxes for nearly 30 years for automobiles and commercial vehicles.

The manufacturing process of the gear-boxes at Opel is carried out running 68 machine tools in two shifts (three axes machine tools for milling, drilling, thread cutting, etc.) which are identical in construction. Two categories of machines are distinguished: the machines operating along the critical path and the machines operating on side-paths. Machine failures along the critical path lead to a breakdown of the entire production line whereas the failure of machines operating on side-paths can be compensated using substitutive machines.

Currently, the maintenance strategy is roughly separated into strategies for machines along the critical path and machines producing on side-paths. For machines along the critical path fixed

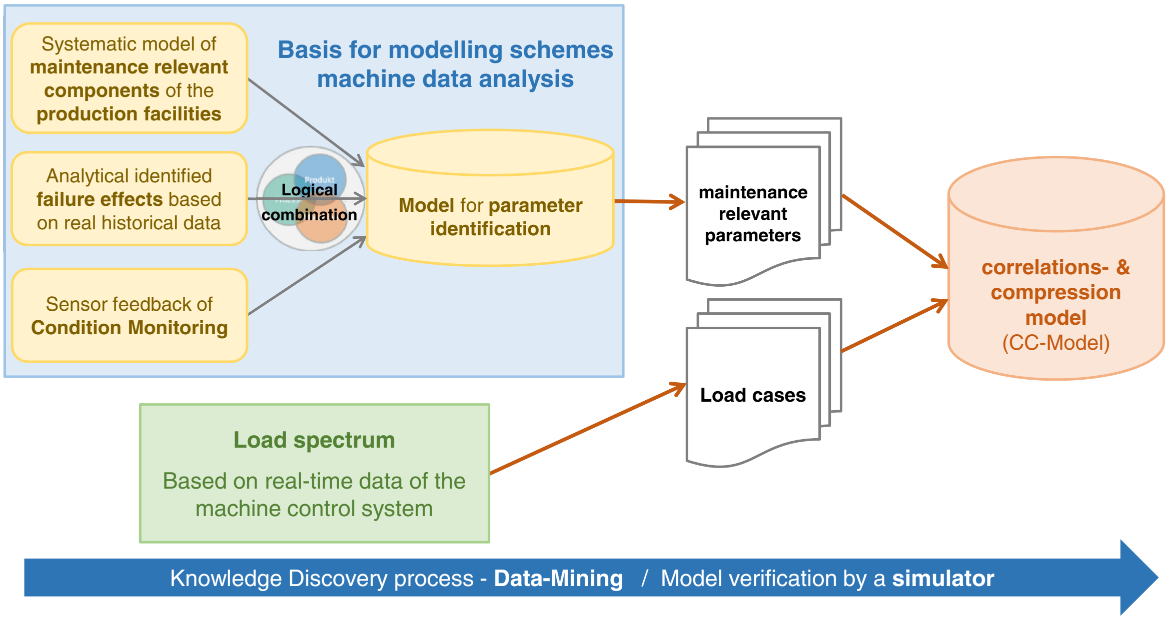

Fig. 21. Linkage of various data-sets [96].

preventive maintenance measures are carried out such as the vibration analyses (every 6 months) or tool monitoring for pointing out tool wear. Moreover, the spare part management separates the "parts in stock" (along critical path) from the "parts ordered on demand" (after machine failure on side-paths).

The currently implemented maintenance management consists of heterogeneous tools and methods among different working areas, manually edited maintenance lists, uses non-uniform language regarding maintenance and non-holistic systems for collecting, processing and evaluating maintenance data.

In order to better anticipate and forecast machine failure moments an innovative maintenance approach (compared to the existing condition based and periodic maintenance) is being developed using 6 of the 68 machines as a reference. First, various data related to condition monitoring, product quality and maintenance history are collected from the existing heterogeneous maintenance tools (Fig. 21). By depicting the production facilities on component level a basis for linking this data is created.

Based on this data input (coming from sensor feedback, from analytically identified wear effects based on real historical data and from a systematic model for maintenance of relevant components of the production facilities) parameters relevant for anticipatory maintenance are identified. Parallel, real-time data of the load spectrum coming from the control system are collected. In a next step, the maintenance relevant parameters and the currently occurring load cases are matched to derive conclusions concerning load-induced wear and quality deviations. Data mining methods enable a semi-automatic and rule based data correlation and compression. Finally, a reaction model is suggesting anticipatory quality and maintenance measures by an integrated set of rules.

The result of the project is a maintenance control centre for production lines. Thereby the maintenance control centre is based on an anticipatory maintenance strategy, supporting best possible product quality, optimized plant availability and reduced maintenance costs. At the same time, it allows quick responses to failure moments. Thus, it is possible to plan rule based anticipative maintenance measures, combined in a reaction model, performing a multivariate optimization of maintenance and repair measures.

6.8. Cross-company information exchange for an adaptive production control based on early warning information

Manufacturing companies are facing a turbulent market environment. Therefore, they focus on their core competencies and reduce their vertical integration. This makes them more vulnerable to disruptions in their supply chain. In this context, the integration of modern auto-ID technologies, e.g. RFID technology, leads to a high level of information transparency in the supply network and thus enables companies to deal with complexity and react to disturbances [137,143,144].

Within the scope of the research project RAN-RFID-based Automotive Network [8] a hybrid RFID reference architecture has been developed to enable a cross-company information exchange and a high level of information transparency in the supply chain. The data, generated by RFID-events, are to be distinguished in organizational data (e.g. order number) and product specific data (e.g. quality features). The cross-company information flow is realized by central and local elements (Fig. 22). The local elements are data bases, so called Event Repositories (ER) within the relevant companies storing the data of every RFID event. The central element, the so called InfoBroker (IB) organizes the cross-company information exchange according to predefined rules of each supply chain member [144,141].

The cross-company information flow facilitates the implementation of an event based disruption management system that can react on early warning information and thus reduce the consequences of disruptions in the supply chain for the Original Equipment Manufacturer (OEM). Therefore, each RFID-event generated in the factory of the supplier, is analyzed and evaluated with regard to its criticality for the OEM. If a critical event has been detected the OEM is informed by early warning information. So the cross-company information exchange extends the time period

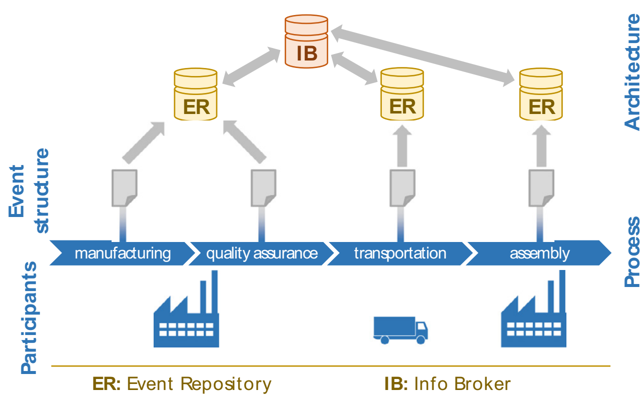

Fig. 22. Reference model overview [144].

during which the OEM can react to the future disturbance and thus reduces their consequences within its own company. The event based disruption management system was evaluated by the simulation of a prototypical implemented production system. It consists of an OEM producing a high variety product (gearbox) and two Tier-1 suppliers (gears and gearbox components). The components for the gearbox are produced immediately before the assembly date in the suppliers' factories and are delivered to the OEM. This allows small time and stock buffers in the supply chain leading to a high dependency between the supply chain members. The simulation proved that the additional amount of time generated by the early warning information decisively contributes to improving the focused logistics objectives. So the adherence to delivery dates of the production system for example could be increased by 5% compared to a conventional disruption management system which cannot rely on an early warning created by an intelligent product [144].

Besides the safeguarding of production processes through cross-company information exchange, the developed RFID reference architecture in combination with the integration of RFID technology enables an adaptive production control within the company. The real situation on the shop floor can be derived by the data which has been generated by the smart products and stored in a company-owned, centralized database. This additional information is the basis for adaptation decisions concerning the production plan. This component of the reference architecture has been realized in the company of a German automotive supplier. It produces two fundamentally different variants of seats which differ distinctively concerning configuration, lot size and throughput time. The final assembly is carried out on two parallel running assembly lines. The respective components are mounted on variant-neutral preassembly lines. In this complex assembly environment the data, e.g. quality features and order number, are generated by smart products on several predefined points during the production process. The smart products in the supplier's factory are the seat and the backrest which are provided with RFID tags. So the relevant data are carried on and, communicated by the product itself. This enables the Manufacturing Execution System (MES) which is enhanced with an order monitoring module to accordingly adapt the production. The realized decentralized control loops were able to synchronize the assembly of the seats and to reduce stock buffer. Furthermore, it was possible to accelerate rework processes because of the specific data, e.g. quality features, that is carried on the product. This leads to a reduction of throughput time for the final assembly process and to an increased adherence to delivery dates for the entire company [137,143].

6.9. Pilot CPPS for research, innovation and education purposes

An obvious way to develop CPPS related new approaches, to test them in a cyber-physical environment and to demonstrate the results for different stakeholders (granting agencies, industry representatives, students, etc.) is the setting up of pilot systems for research, innovation and education purposes.

The design process of the CPPS/Smart Factory laboratory at the Institute for computer Science and Control (MTA SZTAKI) was initiated in 2011, and is managed by the Fraunhofer Project Center PMI at MTA SZTAKI. The current form of the facility has been gradually built since 2013 [74,75].

Intended to comprise a small-scale (socio-)cyber-physical system, the facility models a production site where aspects like material handling, resource management and agent interaction are represented by physical components. The layout of the equipment is organized around a circle of four conveyor belts of 45 mm width, accessible to four, structurally identical, PLC-controlled workstations, a high bay warehouse, a set of 2–3 mobile robots, and two 6-DOF manipulators (Fig. 23). Workpieces are represented by RFID-equipped resin castings which receive blank paper inlays that undergo processing steps at the workstations.

Fig. 23. The SMART Factory at SZTAKI [75].

The latter include drilling/punching with resources permanently allocated to each workstation, and stamping with ink dispensers implemented as a movable resource that is delivered to the workstations as demanded by the pending operations.

Individual control units are connected via an architecture of CAN and LAN connections, while the mobile robots use WLAN. Functional units are individually accessible and represented as agents in an agent container running on a central host which can be connected to further virtual subsystems and receive commands and data from other higher level sources, such as scheduling algorithms. Interaction with human operators is supported by a rich assortment of interfaces, including 3D imaging, a large touch screen, local pendants, etc.

The infrastructure and functionalities of the Smart Factory are still in development with regard to the hardware and control (completion of workstation and logistics functionalities and agent representation), the human–machine interaction (high level integration of existing components, access points for NFC enabled smart phones for direct interaction with workpiece tags), and the remote coupling with virtual subsystems.

6.10. Guided support in company specific CPPS/Industrie 4.0 strategy development

While realizing the potential of the CPPS/Industrie 4.0 concepts today's manufacturers experience substantial problems in bringing visionary ideas down to the shop floor. In general, difficulties occur mainly due to different perceptions about the principal nature of these new concepts, the broadness and complexity of related topics, the expected impact on the strategic and operational level and – as an inevitable consequence – the concrete measures needed to transform towards a CPPS-ready company. The above outlined experiences have been collected by the Austrian research institution Fraunhofer Austria through a series of Industrie 4.0 strategy development workshops and personal interviews with senior management (alternatively one can say: kick-off workshops) that were conducted in several Austrian based manufacturing companies. The experiences gained through these workshops and interviews were used for developing a three-stage model that systematically guides companies in their "Industrie 4.0" vision and strategy finding process (Phase 1 in Fig. 24).

The main goal of the model illustrated is to guide companies in developing their own specific Industrie 4.0 vision along with a strategic roadmap to reach it. According to the model built upon the concepts of co-innovation and technology road mapping, a company needs to go through three stages (Envision → Enable → Enact) to arrive at its own Industrie 4.0 vision and strategy roadmap.

Within the "Envision" stage a company acquaints itself with the general concepts of CPPS, develops its own understanding and

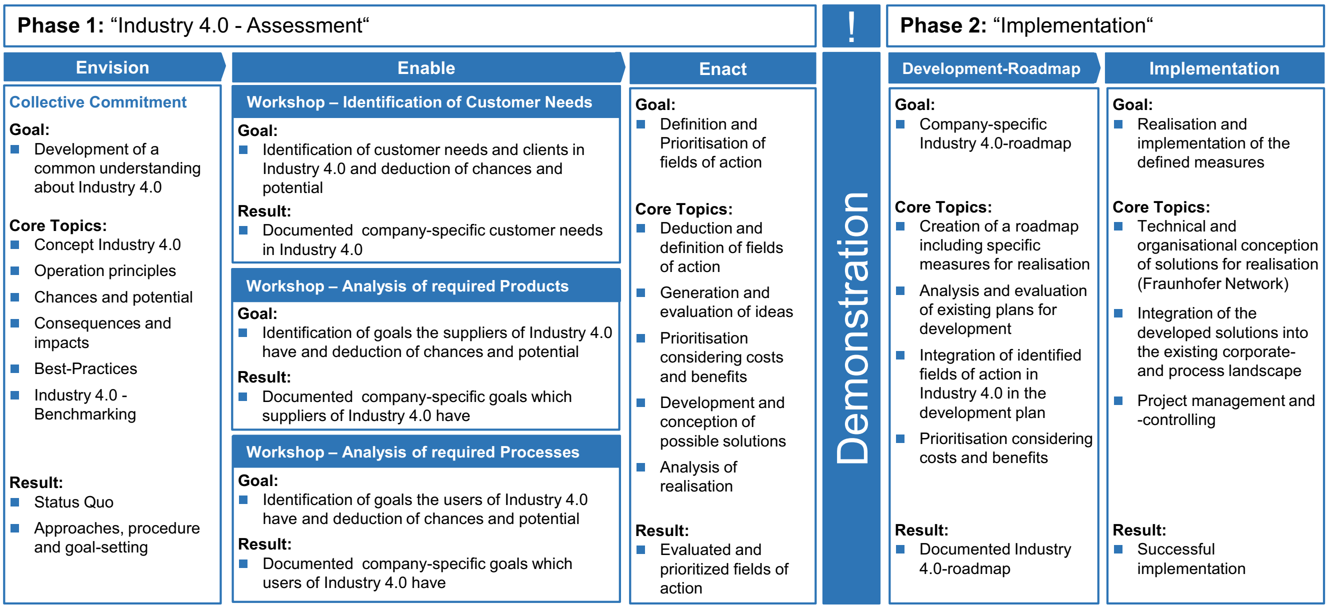

Fig. 24. Three-stage model for guiding companies in developing their own specific Industrie 4.0 vision and roadmap.

aligns general ideas with company specific objectives and customer needs. The goal of this stage is to arrive at a company tailored Industrie 4.0 vision that takes into account peculiarities of the industry and the company environment. Stakeholders from top management are primarily involved but also important business partners are invited to take part in this phase.

Broad commitment to the outcomes is reached through a participative approach where members of middle management are actively involved in vision development. At this stage also external experts are involved to present relevant best practices and to give important impulses towards vision building.

The "Enable" stage is dedicated to develop principal strategies (fields of action) towards the previously defined Industrie 4.0 vision. This is mainly accomplished by using roadmapping techniques. During this stage the abstract yet company specific vision of Industrie 4.0 is broken down into more concrete and measurable company specific objectives and goals. In the model a distinction between three principal strategic areas – the customer, the product and the process – is suggested. For these areas and related objectives, strategies are developed that answer the question what has to be done to achieve them. Both objectives and strategies need to be settled against external constraints such as time, technology, legal and society issues, natural resources. In order to facilitate the strategy planning and alignment process, "strategic road-mapping" – a visualization and structuring technique – is used. Road-mapping allows a company to sketch both envisaged strategies and external constraints on separate layers against a common timeline.

Finally, the "Enact" stage has the goal to transform strategies into concrete projects. Thus, project goals, teams and principal milestones have to be defined. Projects are subsequently evaluated and prioritized against the resources available, potential risks and impact. Projects can be as well integrated in the previously high-level strategy roadmap and therefore complement the yet abstract strategic perspective with a concrete map of planned activities.

The execution of the stages according to the above model results in a company specific roadmap enabling a company to clearly communicate its Industrie 4.0 vision and strategy internally but also externally towards its important stakeholders. The implementation Phase is indicated on the right side of Fig. 24.

7. 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.

As to the main R&D challenges on the side of CS and ICT the following literature can be referred [16,19,20,25,39,54,67,76,77,83,84,82,125,131,181], here only four fundamental ones with general importance are outlined:

- Appropriate *handling of time* in programming languages, operation systems, and computer networks.
- Development of *computational dynamical systems theory*. Namely, the behaviour of the physical parts of the systems can be modelled, simulated and analyzed using methods from continuous systems theory while the cyber part by computational systems theory (e.g. computability, complexity). Hybrid solutions in this sense are required.
- *Standardization* in the CPS field. Standardization is of crucial importance and it necessitates wide range cooperation activities involving the main players of the ICT field. Without standardization only isolated CPS solutions can be developed.
- *Security issues* in the cyber-physical system era. CPS consist of various hardware and software parts working together. In addition to hardware and software security, operational issues are also required to be considered for safety and dependability reasons.

In the following enumeration only a couple of the R&D challenges are outlined from the much bigger set of research fields which are related to CPPS [27,35,41,79,86,106,105,126,146,213]:

- *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, the 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 fuse assembly features and sensor measurements and fast search algorithms to adapt and compensate dynamic changes in the real environment is required.

8. Economic potentials of CPPS

Intelligent and connected products are going to cause changes in the way value is created but also changes in the competitive environment. Increases in productivity and huge progress concerning performance and functionality of products are possible [15,133].

Regarding the digitization of the manufacturing industry through Industrie 4.0 there will be tremendous economic and organizational effects. Ref. [176] expects the economic value of the Internet of Things to reach 1.9 trillion dollars worldwide in 2020 and at the same time the costs of processors are going to decrease down to about one dollar. Just the supplier ecosystem of Industrie 4.0 solutions is expected to reach 420 Billion Euros in value by 2020 [45]. The use of connected devices in manufacturing systems is supposed to trigger productivity gains equivalent to 2.5–5% [92] and 60% of manufacturing companies think that Industrie 4.0 is going to enable them to increase their revenues by implementing new business models [89]. Almost every (80–100%) manufacturing facility could be using connected devices by 2025 and there is a potential economic impact of 900 billion to 2.3 trillion dollars in cost savings per year by 2025 [92]. Furthermore services based on connected devices represent the majority of industrial services in 2020 with 17.5 billion Euros per year.

The biggest changes happen where cyber-physical systems cause disruptive innovation. This development requires strong interdisciplinary partnerships between IT and manufacturing companies, which will strengthen the links in existing ecosystems [48,176]. Companies, consumers and products will be massively interconnected due to digital networks, which lead to increased network effects and a joint value creation in ecosystems [65]. To be more specific, it is highly important for manufacturing companies to establish connections to experts in the field of sensor technology and connectivity. Moreover software companies can help to effectively use the potential of cyber-physical systems [60]. In conclusion the whole ecosystem is needed to exploit the full potential of CPS and value is created by closely connected companies which communicate in real time [147]. But there is also the potential of new players entering the market where IT meets manufacturing competencies by offering the customer a direct benefit instead of products, which happened before during other technology waves [12,93]. Paying per availability, productivity or value by using the features offered by CPS are examples that can be named in this context [90]. Right now companies are capturing only 20% of the value digital means provide [97].

9. Conclusions

In this paper the parallel developments in computer science (CS) and information and communication technologies (ICT) on one hand, and in manufacturing science and technology (MST) on the other, were highlighted, pointing out their mutual influence. The concepts of CPS and CPPS were introduced in short, together with the high expectations towards them. The MST 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 CPS and CPPS were also highlighted.

It can be stated that – as result of the R&D&I activities of the past decades – the MST community has paved the way for a relatively smooth entry into the CPPS era. Many concepts – some of them were enumerated in Section 4 – can be put into the real practice by using the enabling technologies offered and promised by CPS, as it was highlighted in Sections 5 and 6.

Without any question, CPPS can be considered as an extremely important step in the development of future manufacturing systems. However, in order to actually realize at least a portion of the partly exaggerated expectations, significant further R&D&I activities are needed. In parallel, the socio-ethical aspects of CPS and CPPS are also to be comprehensively investigated.

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