Review:

"Industrie 4.0" and Smart Manufacturing – A Review of Research Issues and Application Examples

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A fourth industrial revolution is propagated in global manufacturing. It is based on the introduction of Internet of Things and Servitization concepts into manufacturing companies, leading to vertically and horizontally integrated production systems. The resulting Smart Factories are able to fulfill dynamic customer demands with high variability in small lot sizes while integrating human ingenuity and automation. To support the manufacturing industry in this conversion process and enhance global competitiveness, policy makers in several countries have established research and technology transfer schemes. Most prominently, Germany has enacted its 'Industrie 4.0' program, which is increasingly affecting European policy, while the United States focus on Smart Manufacturing. Other industrial nations have established their own programs on Smart Manufacturing, notably Japan and Korea. This shows that manufacturing intelligence has become a crucial topic for research and industry worldwide. The main object of these activities are so-called Cyber-Physical Systems (CPS): physical entities (e.g. machines, vehicles, work pieces etc.), which are equipped with technologies such as RFID, sensors, microprocessors, telematics or complete embedded systems. They are characterized by being able to collect data of themselves and their environment, process and evaluate this data, connect and communicate with other systems and initiate actions. In addition, CPS enable new services that can replace traditional business models based solely on product sales. The objective of this paper is to give an overview of Industrie 4.0 and Smart Manufacturing programs, analyze the application potential of CPS, starting from product design, through production and logistics, up to maintenance and exploitation (e.g. recycling) and identify current and future research issues. Besides the technical perspective, the paper also takes into account the economic side with the new business strategies and models made possible.

Keywords: Industry 4.0, Smart Manufacturing, Cyber-Physical Systems, Industrial Internet, Smart Factory

1. Introduction

Three industrial revolutions have led to paradigm changes in the domain of manufacturing so far: mechanization through water and steam power, mass production in assembly lines, and automation using information technology. However, over the past years, industry, together with researchers and policy makers worldwide have increasingly advocated an upcoming fourth industrial revolution (see Fig. 1.).

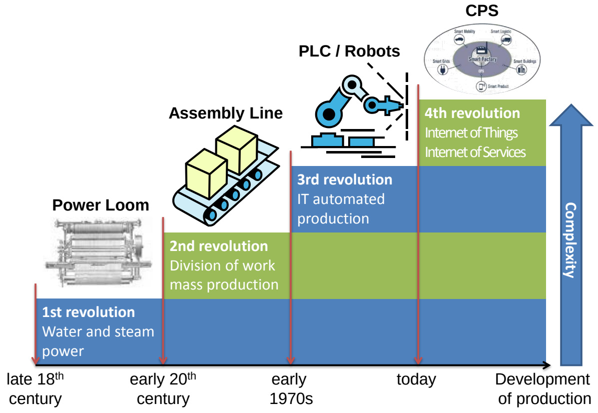


Fig. 1. Four Industrial Revolutions

For example, the German government promotes the computerization of manufacturing industries in their 'Industrie 4.0' (I4.0) program [1,2], while in the United States Smart Manufacturing initiatives, like, e.g., the Smart Manufacturing Leadership Coalition (SMLC), drives and facilitates the broad adoption of manufacturing intelligence [3]. Other major manufacturing countries, like Japan [4] and Korea [5] have also established national programs on Smart Manufacturing.

The fourth industrial revolution is characterized by the introduction of the *Internet of Things* (IoT) and *Internet of Services* concepts into manufacturing, which enables *Smart Factories* with vertically and horizontally integrated production systems. In this world, highly flexible processes that can be changed on-the-fly enable individualized mass production. Variants are self-determined through items delivering their own production data to intelligent machines [6], which are aware of the environment, exchange information and control processes in production and logistics themselves. Data is collected along the whole life-cycle in large quantities and stored decentralized to enable local decisions, but still transparent to be exchanged with partners. In order to realize this vision, elements like machines, storage systems and utilities need to be able to share information, as well as act and control each other autonomously. Such systems are called *Cyber-Physical Systems* (CPS) [7].

CPS emerge through the complex networking and integration of embedded systems, application systems, and infrastructure, enabled by human machine interaction. In contrast to conventional systems used for production or logistics, CPS can be seen as *systems of systems*, which require the collaboration of different disciplines such as mechanical engineering, electrical engineering, and computer science for their realization [8].

The industrial transformation associated with the Smart Manufacturing revolution and the introduction of CPS creates numerous challenges for organizations, technology and employees. All in all, as illustrated in Fig. 1., complexity in production has increased with each industrial revolution. Dynamic socio-technical systems have emerged, that consist of a great number of tangible, intangible and also human elements. This complexity has to be managed by appropriate methods and tools. Furthermore, the interaction between humans and machines requires the right interfaces and concepts to be efficient and safe. New and innovative services are possible based on CPS technology, but they also need new innovative business models to be profitable [9].

I4.0, Smart Manufacturing and the other initiatives aim to provide the foundation to overcome these challenges and support manufacturing companies and their stakeholders in their transition to Smart Manufacturing. They aim to develop and deliver appropriate models, methods and tools for manufacturing companies, as well as establishing prototype implementations that can be used as exemplary blueprints for other companies that are interested in this development.

The objective of this paper is to give an overview about these initiatives, with a focus on I4.0 and Smart Manufacturing, and provide selected application examples. Based on the results, current and future research issues for Smart Manufacturing will be identified. The next chapter (2) introduces the scope and methodology of the review, while chapter 3 describes the different initiatives. Chapter 4 illustrates application scenarios and research issues and the paper is concluded in chapter 5.

2. Scope and Methodology

The scope of this review comprises an overview on current smart manufacturing initiatives, research issues and application examples. This includes trends in manufacturing to utilize the Internet of Things and related services, as well as the resulting industrial practices. In this paper, Smart Manufacturing refers mainly to the use of intelligent machines, so called Cyber-Physical Systems that are networked, context-aware and self-controlled. The focus of the review lies on the European, specifically German, Industrie 4.0 initiative and Smart Manufacturing activities in the United States. Other programs, e.g. in Japan and Korea (Smart Factory) are recognized, but not analyzed in detail.

The methodology of the review is based on two pillars, a literature review on the state-of-the-art in Smart Manufacturing and I4.0, as well as studying application scenarios from research and industry. For the literature review, fundamental official publications from the initiatives have been taken into account. Additionally, relevant papers identified through title, abstract and keywords from interdisciplinary search engines such as SCOPUS have been analyzed. Regarding the application scenarios, light-house projects from research and industry, in some of which the authors are directly involved, have been studied in order to identify current and future research issues.

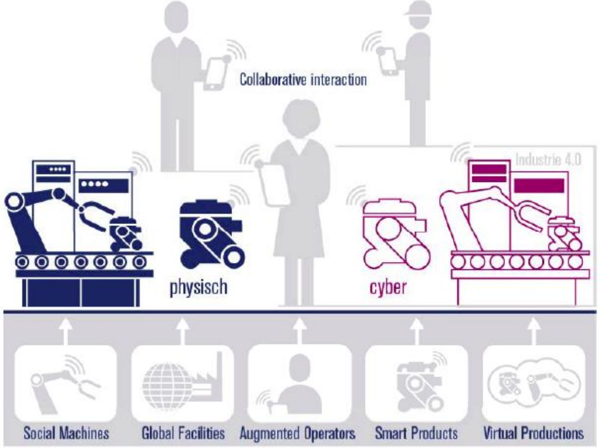
3. Definitions and Frameworks

This section introduces definitions and frameworks in the scope of Smart Manufacturing. First, the main initatives of Industrie 4.0 in Germany and Smart Manufacturing in the United States are presented. Following, other initiatives and related terms are described.

3.1. Industrie 4.0

For Germany, having one of the most competitive manufacturing industries in the world and a strong machinery and plant fabrication, it is vital to master the challenges of a fourth industrial revolution. Therefore, the German government has established its Industrie 4.0 program [1] to keep Germany a manufacturing country. It is based on the assumption that *"industrial production in the near 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 that leads to so-called hybrid products"* [11].

I4.0 comprises a paradigm shift from automated manufacturing towards an intelligent manufacturing concept. Physical and virtual world grow together and objects (incl. machines) are equipped with sensors and actuators [10]. The intelligent manufacturing implementation will make use of concepts like the Internet of Things to facilitate this change. The exclusive feature in I4.0 is to fulfill the individual customer requirements with product variants in a very small lot size, down to one-off items [2]. Availability of all relevant information in real-time will enable the manufacturing system to meet customer requirements without waste for re-configuration of assembly line or set-up times through dynamic business and engineering processes (see Fig. 2.).



Source: Final report of the working group Industrie 4.0 [1]

Fig. 2. CPS Vision for Industrie 4.0

In this context, the Smart Manufacturing and logistics systems can not only generate the optimal value stream to fulfil the real-time demands, but also create new business models based on better predictive maintenance, robustness in product design and adaptive logistics.

Industrie 4.0 addresses research and development actions in eight key areas to support the adoption of its principles in industry [1]:

i. *Standardization and reference architecture:* Collaborative partnerships of organizations in value networks requires a set of common standards in a reference architecture.

ii. *Managing complex systems:* The higher complexity of systems and products require appropriate models for their management.

iii. *A comprehensive broadband infrastructure for industry:* The Internet of Things requires a reliable and fast communication network infrastructure.

iv. *Safety and security:* Related to close human-machine interaction, manufacturing systems must not harm people or the environment. Furthermore, data and information need access authorization and privacy measures.

v. *Work organisation and design:* Along with the machines, also the environment and processes of work will change, giving the employee greater freedom and responsibility.

vi. *Training and continuing professional development:* In relation to the previous key area, the worker needs to qualified through suitable training and life-long learning.

vii. *Regulatory framework:* Together with the organizational changes, also legislation has to take new innovation into account, especially for privacy and liability regulations.

viii. *Resource efficiency:* By improving productivity and resource efficiency, consumption of raw material and energy should be lowered.

Along with the actions in the key areas, manufacturing companies have to develop new business strategies for I4.0. Value networks and profit / loss sharing will be strongly linked to the individual customer problem. Responsibilities and privacy rules are described in Service Level Agreements (SLA) [1].

In Germany, the federal government has been funding the research agenda Industrie 4.0 through several programs during the last years. While the Federal Ministry of Education and Research has published seven calls with an overall funding of € 120 million, the Federal Ministry for Economic Affairs and Energy has funded projects with another € 80 million [12].

3.2. Smart Manufacturing

Smart Manufacturing is a term coined by several agencies like the Department of Energy (DoE) and the National Institute of Standards and Technology (NIST) in the United States. Wallace and Riddick [13] describe Smart Manufacturing in short as "a data intensive application of information technology at the shop floor level and above to enable intelligent, efficient and responsive operations". While there are multiple more comprehensive definitions available (e.g. [14]), they all highlight the use of Information and Communication Technology (ICT) and advanced data analytics to improve manufacturing operations at all levels of the supply network, be it the shop floor [15], factory [16] or Supply Chain [14,17]. Some authors go even a step further and extend the Smart Manufacturing framework beyond manufacturing itself, highlighting the lifecycle perspective [18]. This broad focus already highlights the close proximity to other established areas like Industrie 4.0 (see previous section) and Intelligent Manufacturing (Systems) [19].

Smart Manufacturing incorporates various technologies, including but not limited to CP(P)S, IoT, robotics/automation, big data analytics and cloud computing [20,21] to realize the vision of a data-driven, connected supply network. An important aspect that differentiates Smart Manufacturing from many other initiatives, is the specific emphasis on human ingenuity within the framework. Humans are not to be simply replaced by Artificial Intelligence and automation on the shop floor but their capabilities are to be enhanced by smartly designing the customized solution for the specific area. The importance of product and process information and data, enabling technology and (human or machine inherent) knowledge is commonly accepted. Highlighting the broad and comprehensive scope of Smart Manufacturing, its three main pillars are [14]:

- Plantwide optimization
- Sustainable production
- Agile supply chains

In the United States, several federal funding agencies have calls for funding placed to drive Smart Manufacturing. For example, the DoE has announced up to US$ 70 million in funding in Smart Manufacturing [22], NIST had several calls for their Smart Manufacturing program with a budget of ca. US$ 30 million per year. Several other initiatives offer additional opportunities in this area or closely related ones, like the Smart Manufacturing Leadership Coalition (SMLC) or NSF’s Cybermanufacturing program.

3.3. Other related terms and initiatives

Intelligent Manufacturing / Intelligent Manufacturing Systems (IMS): Intelligent Manufacturing is sometimes used synonymously to Smart Manufacturing. While the close collaboration of the IMS organization with the several Smart Manufacturing funding agencies and research institutions support this, there is a notion that Intelligent Manufacturing may focus more on the technical aspects and less on the organizational ones. Kumar’s [19] definition of an intelligent manufacturing process as having “the ability to self-regulate and/or self-control to manufacture the product within the design specifications” shows that at least some researchers see Intelligent Manufacturing more focused on the analytics and control aspects. However, the original definition from the later 1980ies by Yoshikawa [23] emphasize the importance of humans within the system as well, supporting the similarity to Smart Manufacturing.

Smart Factory: Smart Factory is a term used in different contexts for some time. Some might argue that Smart Factory is focusing more on the individual entity (plant level) [24–26] rather than the broader supply network scope of Smart Manufacturing and Industrie 4.0. In this case the Smart Factory paradigm relates strongly to IIoT and CPS [27]. However, other sources refer specifically to the Industrie 4.0 initiative as the basis for the Smart Factory movement [5,28], with the Korean Smart Factory initiative being at the forefront. Furthermore, the National Science Foundation (USA) has issued a joint call for proposals with the Korean National Research Foundation (NRF) specifically aiming at collaborations including the Smart Manufacturing domain, which indicates that the broader perspective is shared by Smart Factory and that the program’s scope is similar to Smart Manufacturing and Industrie 4.0.

Internet of Things (IoT) / Industrial Internet of Things (IIoT): Intelligent Manufacturing and Smart Factory paradigms may be argued to be similar to Smart Manufacturing and Industrie 4.0, the Internet of Things (IoT) paradigm is more ICT oriented [29]. IoT’s vision of ubiquitous computing [30] is to ‘connect’ the physical world with the virtual world and facilitate communication between all connected entities [31,32]. IoT requires its physical entities to have certain amount of ‘smarts’ incorporated, in the sense of communication, data processing and/or sensing capability. In recent years, a sub-paradigm, the Industrial Internet of Things (IIoT) emerged, focusing on the interconnectivity of industrial assets, like manufacturing machines, tools and logistics operations [33]. In this understanding, many of the basic requirements are similar to the ones faced by Smart Manufacturing and Industrie 4.0, e.g., the challenge of interoperability and privacy/security issues [34]. Overall, IoT/IIoT can be understood as an enabling technology similar to CP(P)S [20,35].

Industrial Internet: The industrial Internet is understood as the unity of (industrial) machines and software [36]. Their global outlet is the Industrial Internet Consortium (IIC) (www.iiconsortium.org). This basic understanding highlights the similarity towards CP(P)S and Industrial Internet of Things (IIoT) [37] as a more technology focused framework. Some argue that the main difference between the Industrial Internet and Smart Manufacturing and Industrie 4.0 is the more focused scope, mainly looking at the machine and maybe shop-floor level instead of the overall supply network [38]. Others understand the Industrial Internet as the foundation for system wide optimization [36].

4. Applications and Research Issues

In this section, two main topics are discussed. Firstly, selected application scenarios and use cases of Smart Manufacturing are presented. Derived from the selected application scenarios and enhanced by literature and experience of the authors, current and future research issues in the context of Smart Manufacturing and I4.0 are discussed thereafter.

4.1. Application Scenarios & Use Cases

The selection of application scenarios was made to present a broad variety in order to highlight the wide scope of the initiatives. The application cases range from technical initiatives implementing CPS in SME intralogistics [39], over human robot interaction at the shop-floor level using sensors and image recognition [40], to new business models around product enhancing services based on lifecycle and sensor data [41].

4.1.1. Cyber-Physical Logistics System

The case company in this application scenario is a gear manufacturer from one of the first I4.0 lighthouse projects in Germany that has organized its processes according to the principles of lean production. Stocks in production are kept at a low level despite a high number of variants and intralogistics are managed by a container-Kanban-procedure in combination with a milk run. For every machine, there is a delivery space where only one floor roller (transport unit for several load carriers) for exactly one production order can be placed, and also one pick up area. A human operated electric train services the machines every hour to pick up finished orders and deliver supplies. The machines are arranged in such a way that the train can reach all machines by driving an "eight" course. At the intersection of the loops, it is also possible to turn to the area for incoming and outgoing goods. Each full hour all stations are service, picking off finished orders, distributing them and noting which delivery areas are empty. These free delivery spaces are equipped with orders from the buffer stock in the following cycle. The fixed cycle time leads to a high fluctuation in floor roller usage and waste of electric train capacity. The complete loops are always serviced, although there might be no need for transport, as there is no up-to-date information about collection and delivery orders.

A cyber-physical production system has been established, featuring a cyber-physical logistic system (CPLS), to increase the efficiency of lean production in this scenario, with many variations of products and not completely levelled and synchronized production lines. The aim of the CPLS is to increase the flexibility through autonomous decisions and enable a reduction of inventories due to the autonomous solving of errors in real time. The demand-driven milk run is based on information about the occupancy of the delivery and pick up spaces. Furthermore, cyber-physical load carriers (CP-LC) with sensors to locate themselves and to monitor the environmental conditions (e.g. temperature, acceleration) which are affecting the components have been introduced (see Fig. 3.).

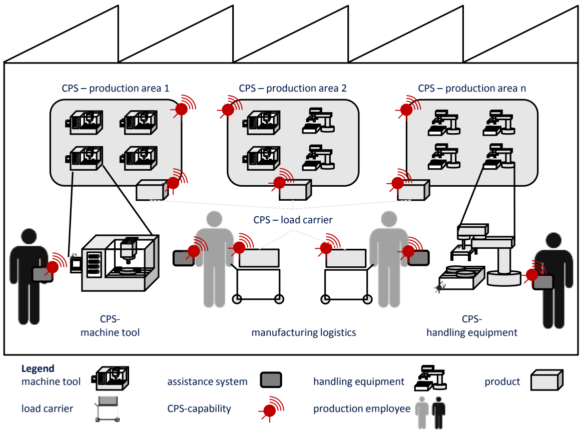


Fig. 3. Scenario of the Cyber-Physical Production System (following Reinhart et al. [42])

The CP-LCs can communicate with other cyber-physical systems and can transmit their position to the intralogistics employee. In this way he gets the information where delivery or collection needs are before starting a new cycle. For this purpose, a tablet PC is chosen on which the current needs are displayed. On this device, the remaining processing times of the machines and logs of operational data are considered to estimate the completion dates of the current production orders and thereby calculating the optimal departure time. The employee can now decide based on this information when he starts the next tour. Under the restrictions that the machine must not run "empty" and that only one order can be placed on the delivery space of the machine, the number of cycles and loops is lowered through networking the individual logistics units, reducing transport and motion processes to a minimum. The reduction of cycles of the milk run has measurable advantages for the productivity of the case company, because they have more time for their core activities in commissioning, shipping and storage. According to a simulation based on the current capacity of the electric train, the number of cycles can be reduced by approx. 68 %, while the number of driven loops in the cycles can be reduced by about 27 %.

4.1.2. Safe Human-Robot Interaction

Smart Manufacturing is different from the pure automation focus of previous initiatives. For a smart robotics' factory within the context of I4.0 and IoT, where high productivity is demanded by the market, collaboration between human workers and robots is the key. Human workers are essential in their role of either supervisor, collaborator and for jobs robots are not trained or capable of. These so called co-bots (collaborative robots) [43] are a dedicated area of research and several companies already brought forth their vision of such systems.

The constant human presence in or near the robot's work area forces companies to rethink how a robotic work space is organized and shared with its human counterparts. Traditionally, the robotic work area was fenced of and prohibited for the humans to enter during operation due to safety concerns (see Fig. 4.).

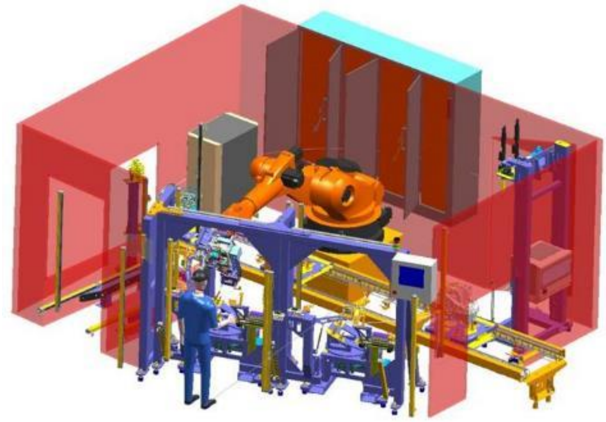


Fig. 4. Traditional protection solution

Within the I4.0 initiative, the presented application research focuses on new ways to a) ensure the safety of human workers and b) limit the restrictions of a divided workspace. The core of this robotic factory CPS development is the integration of dynamic characteristics of the individual components. The individual protection components register context, situation and status of worker, machine, plant and process and activate protective mechanisms before a hazard, e.g. collision, can occur. The production process will run without threats and interruptions and this will achieve the level of security and safety, meeting worker safety legal requirements on the shop floor. Symbiotic human–robot collaboration [37] is defined for a fenceless environment in which productivity and resource effectiveness can be improved by combining the flexibility of humans and the accuracy of machines. Robotic CPS can enable such human–robot collaboration with the characteristics of dynamic task planning, active collision avoidance, and adaptive robot control. Humans are part of the CPS design, in which human instructions to robots by speech, signs or hand gestures are possible during collaborative handling, assembly, packaging, food processing or other tasks. All of these industrial tasks bring the focus of current research to human robot collaboration on heavy payload robots. The approach is to exhibit safe intermediate Human-Robot Collaboration (HRC) without any fencing. In order to realize this, extra safety and protection measures need to be implemented for a collaborative robotic cyber physical system (CPS) (see Fig. 5.).

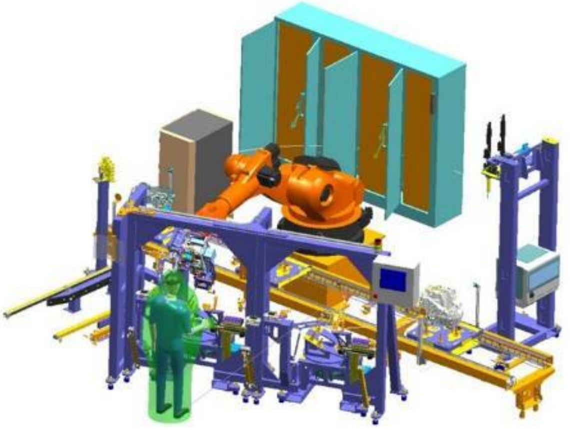


Fig. 5. CPS protection solution

The human component is well connected through different adaptor technologies, e.g. human position tracking, and safety distance parameters are important considerations for worker safety in the robotic CPS. The robotic CPS is a highly automated system as it removes the boundaries between the composite elements and supporting their operational interactions; thus achieving a truly smart system with humans in the loop, enabled by connected entities that are able to sense, interpret and react.

4.1.3. Video Surveillance as a Service

This application scenario describes a use case from an ongoing European research project on Servitization of manufacturing. The case company is a vendor for the aviation sector, which offers fully integrated solutions for surveillance systems. This Aircraft Security Video System (ASVS) is an integrated, video-based infrastructure. As a modular solution, the system consolidates several components, all of which are required by a universal surveillance system for aviation. The focus of the use case is on the Cabin Video Surveillance System (CVSS), which helps flight attendants to monitor the cabin area while the aircraft is in flight. It generates video streams, which are stored on a memory cartridge within the Central Video Unit (CVU/DVR). These systems are customized, individual turnkey solutions, certified according to aviation standards and approved by aviation authorities. Customers are airlines, which retrofit their aircraft with the buyer furnished surveillance solutions from the vendor. In general, the design, manufacturing, operation and maintenance of aircraft and (airborne) aircraft equipment are strictly regulated by authorities (mainly EASA, FAA and local authorities), which means that in the case of changes the system has to be re-certified, which is a long and expensive process.

The company offers a Ground Station as extension to the ASVS, which only allows viewing video data or searching and exporting specific chunks of it. It doesn't have to be certified, as it is not part of the "flying equipment" and can thus be modified more easily. The idea is to transform the Ground Station into a CPS that interfaces with the CVU/DVR to offer a web-based service which archives the video data automatically and offers the access to the video data of an airline on demand via internet. Additional automatic analyses of video streams and logging data can be added in the future to provide even more services for the customer as well as system status data for maintenance (see Fig. 6.).

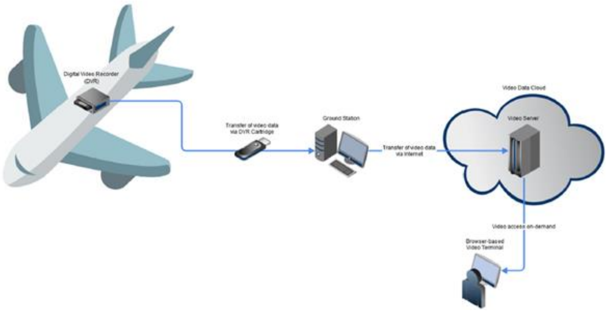


Fig. 6. Video Surveillance as a Service Scenario

The challenge for the company to develop an appropriate CPS is on the one hand to modify and newly assemble the Ground Station for the proposed service. Additionally, a new software will be required to handle the proposed actions for the service. As service engineering has not been the core competence of the company until now, especially support in managing the service life cycle, from ideation over Requirements Engineering and testing, is required. Customer feedback has to be collected in order to improve the service; this information can be also be fed into the ideation phase for additional services.

A major change for the company is the transition from selling their video surveillance solution to providing video archiving and analysis services. In order to make an innovative, but safe shift from a pure product supplier to a product-service provider, there is a need to identify if the service will be accepted by the market, possibly also in other sectors (e.g. train surveillance). Furthermore, it has to be ensured that the service business doesn't cannibalize the product business and is able to generate stable and continuous revenues. Thus, a business model innovation is required to offer the enhanced functionality to the customer.

4.2. Research Issues

In this section, current research issues regarding the adoption of I4.0 and Smart Manufacturing are presented. The identified research issues are structured in three main categories: technical, methodological and business case research issues. Some of the discussed research issues represent aspects that could be grouped within more than one of these categories. In such cases, the grouping is based upon the most significant factor in the eyes of the authors.

4.2.1. Technical Research Issues

Standards/interfaces: In the global economy, supply networks are formed in the majority of cases by a number of heterogeneous entities. Heterogeneous in this case includes different dimensions like, e.g., company size, location, but also the used software solutions. While some companies might choose proprietary solutions available on the market, others might prefer (or are forced to by, e.g., economic means) self-developed or open-access solutions. When companies with different systems choose to work together, the interoperability is a major issue that needs to be addressed to enable Smart Manufacturing. This is e.g. reflected in the CPLS use case, where machines, transport systems and human interface devices from different vendors have to collaborate. Due to the dynamic and complex nature of manufacturing, a 'one of a kind' integration will not suffice but commonly respected standards are needed to facilitate formation and operation of successful Smart Manufacturing supply networks.

Data analytics: Data analytics or Big Data are a core component of the data based Smart Manufacturing and I4.0 initiatives. Data analytics are essential to connect the captured sensor (and other manufacturing/supply chain related) data and the humans in the loop. The increasing degree of automation of Smart Manufacturing Systems with real-time data availability and automated monitoring and control depend on strong algorithms supporting human decisions. The co-bots application case e.g. emphasizes the importance of advanced and reliable data analytics algorithms as it is the foundation of the safe collaboration between humans and robotic systems at the envisioned open shop floor.

Data security issues: I4.0 and Smart Manufacturing are by definition very data focused. With CPS connecting all entities and allowing real-time data capturing and exchange using smart sensors and wireless communication protocols. More and more cloud based services provide additional functionality and accessibility to manufacturing data from outside of the facility. This does however come at a price: with the increase in valuable data and the analytical means to use them, the motivation for external parties with potential criminal intent increases as well, e.g. in the case of aircraft video surveillance. As the manufacturing data is the core of the manufacturing companies' competitive advantage, systems need to be developed to prevent unauthorized access to data. A second data security issue that needs attention is the access to connected machines and control systems from outside the companies. Due to the high level of integration and connectivity, this presents another high priority target for criminal third parties, aiming at e.g., sabotage of the manufacturing processes.

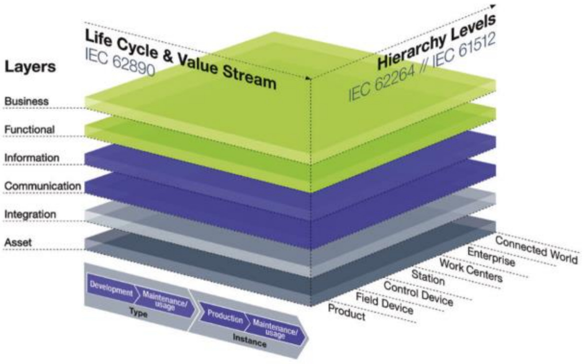
Data quality: While Big Data and other data analytics research streams gain significant attention, the issue of data quality is similarly important [44]. With the increasing amount of manufacturing data available, it presents a challenge to ensure the integrity and quality of the captured and communicated data. Low quality data may lead to results that are endangering the data based optimization and monitoring systems. Automated data quality monitoring algorithms need to be developed and evaluated in a manufacturing environment to support the human users and help to improve the trust in data based decisions. Another aspect of data quality is the heterogeneity of manufacturing data, especially when looking at the whole lifecycle of a product. The annotations of the data entities are very diverse and it is an increasing challenge to incorporate diverse data repositories with different semantics for advanced data analytics. Systems like the Semantic Mediator [45], applied in the CPLS case need to be developed further and included in the standards mentioned before.

Sensors/actuators: With regard to sensing systems, significant progress has been achieved in recent years, regarding quality of measurements, size of the systems and price. However, with the increasing demand of sensors and real-time control of manufacturing processes like in human-robot interaction, also the requirements towards sensors and the systems they are embedded in increased. Reliability, energy consumption and communication protocols are just a few areas where more work has to be conducted for adoption of Smart Manufacturing on a broad scale.

4.2.1. Methodological Research Issues

Reference Models: To enable the description of complex concepts for the migration to Smart Manufacturing / I4.0 and the definition of demands and requirements for specific application domains, reference models are needed. A Reference Architecture Model has been created for Industrie 4.0 (RAMI 4.0) that aims to integrate the different aspects required for dynamic cooperation in value networks. This includes vertical networking of the means of production, the workpiece and the associated data, as well as horizontal networking beyond the single factory towards the formation of dynamic value networks.

In order to integrate all technical and commercial aspects in one model, the perspectives of different application domains had to be understood. Existing approaches have been identified (e.g. IEC 62541, ISO13584-42 or ProSTEP iViP), but cover only partial aspects of the envisaged holistic view. The resulting model contains the main aspects of Industrie 4.0 (see Fig. 7.).



Source: ZVEI, Platform Industrie 4.0 [46]

Fig. 7. Reference Architecture Model Industrie 4.0

Hierarchy levels based on IEC 62264 are extended by a 'Product' and a 'Connected World' level. The life cycle of products and machines is represented horizontally, distinguished between types and individual instances. Finally, six layers describe the IT representation of an I4.0 component in a structured way. Special characteristics of RAMI 4.0 are the combination of life cycle and value stream with a structured approach to define I4.0 components. RAMI 4.0 is about to be standardized as DIN SPEC 91345.

Visualization: Visualization is grouped under methodological issues but has also a strong technical part. Visualization is an important vehicle to communicate the complex results of data analytics to the stakeholders, such as the recorded video streams and operational data from the aircraft surveillance case. It is challenging as the stakeholders have very different foci and requirement towards the visualization and granularity of the presented results. Visualization offers to illustrate the different levels, from very detailed, e.g., machine tool level, to an overview, e.g., supply chain, level. Research and industry need to work together on driving visualization research as it is a critical part of Smart Manufacturing acceptance in real life.

Service/app marketplaces: It has been mentioned multiple times that Smart Manufacturing is an interdisciplinary field, with strong ties between engineering and computer science. App/Service marketplaces gained significant attention in recent years as they offer flexibility, transparency and (in some cases) accreditation/security features. The advances in cloud computing (cloud manufacturing) support this claim. Flexible app/service marketplaces that offer a set of core apps and allow users or independent third parties to develop customized apps focusing on certain issues in the Smart Manufacturing realm are desired by industry and research. User-developed apps can range from granular scheduling apps to advanced supply chain wide data analytics apps. The aircraft surveillance system provider plans to offer advanced video analysis services, some of which could also be developed by third parties. There is a significant overlap with research issue in interfaces/standards, visualization, data analytics, data security and reference models etc.

Requirements Engineering: Inadequate Requirements Engineering (RE) is one of the main sources for the failure of development projects and culminates in exceeding budgets, missing functionalities or even the abortion of the project [47]. Therefore, in the context of Smart Manufacturing, adequate Requirements Engineering is also the key to success or failure of every CPS. Ensuring communication and consistency of requirements for CPS is a challenge due to the variety of stakeholders from different domains involved. Furthermore, viewing CPS as a system of systems, the independence of its elements and their evolutionary nature are challenging. This leads to exceptionally distributed RE activities with isolated RE approaches. In the aircraft surveillance case, the new service engineering department was initially organizationally separated from hardware and software engineering. This complexity leaves requirements fragmented among many disciplines and sometimes conflicting, unstable, unknowable or not fully defined. RE processes need to be able to handle competing stakeholder demands and dynamically respond to continually changing requirements. Finally, the properties of the CPS are not the sum of the properties of its elements. Rather, they emerge from the cumulative interactions of the single systems. Therefore, RE methods and tools have to be able to manage emergent effects with predictable results [48].

Geisberger and Broy [8] emphasize the central role of Requirements Engineering for CPS development, integration, maintenance and evolution. According to their research agenda, main topics in this area include involving users and other stakeholders from different domains actively into CPS development from the beginning, adaption of CPS to needs, habits and competences of the users, specification of formal requirements models, detailing of requirements and mapping them to system elements, integration of mechanical engineering models with digital models from software and systems engineering for the collaborative description of requirements, as well as their implementation, validation, evolution and communication between stakeholders from different disciplines. Penzenstadler and Eckhardt [49] introduce a RE content model for requirements elicitation and documentation at different levels that would have to be adopted by all stakeholders involved. Wiesner et al. [50] propose Natural Language Processing (NLP) as a way to translate non-formal requirements to formal descriptions in different disciplines, thus enabling automated information processing. NLP techniques can assist requirements engineers when writing specifications, transforming requirements in natural language into discipline specific models.

4.2.1. Business Case Issues

Privacy issues: Privacy issues are strongly related to data security issues. However, in this case it was decided to separate the two areas. Whereas data security issues focus more on the technical ability to protect and preserve sensitive (manufacturing) data, privacy issues in this case describe challenges regarding the exchange of data, information and/or knowledge within the company itself and within the supply network. With the dawn of Smart Manufacturing and the connected company, detailed manufacturing data is available for advanced analytics. However, this presents a major thread for the core competencies of specialized manufacturers. By obtaining precious data, competitors are able to not only ‘reverse engineer’ the products but, even more problematic, derive the underlying knowledge and capabilities. On the other hand, within supply networks, companies may work together which are competitors in a different segment of the market. E.g. video data from aircraft surveillance belongs to the airline, is stored by the service provider and is regulated by passenger privacy, with laws differing between countries. Within the supply network, the sharing of information is beneficial for multiple reasons, e.g., quality improvements [51]. Developing mechanisms that ensure that the data is used only for the purpose it is shared requires interdisciplinary research involving, policy, law, business, computer science and engineering experts.

Investment issues: The authors debated if this ‘(initial) investment issue’ should be included in the list as this is a rather general issue which stands true for most new technology based initiatives in manufacturing. However, in this case, the authors believe that the interdisciplinary nature and complexity of Smart Manufacturing installments present (real or imagined) barriers especially for SMEs. Implementing Smart Manufacturing frameworks in a SME, such as the CPLS system, may require a significant investment without a full estimation of the break even point from the start. The reliance on collaboration and the subsequent possibilities of process and organizational improvements are hard to measure. The authors believe that strong Testbeds as put together by the SMLC or Lighthouse projects (I4.0) are a good start to establish benchmarks and successful examples highlighting the potential of such an investment. However, there is a need for theoretical research regarding the quantification and ROI on Smart Manufacturing applications especially for SMEs including the effects of collaboration in complex and dynamic supply networks.

Servitized Business Models: In the manufacturing industry, Business Models (BM) have traditionally focused on the fabrication or assembly of more or less customized (physical) products and have generated revenue from their sales. The therefore required machines, materials and qualified personnel cause high fix costs, so supply chain organization and efficiency have had a high influence on competitiveness [52]. However, these traditional BMs have come under pressure with the global harmonization of technological standards and the reduction of trade barriers. Many researchers have suggested that manufacturing firms in developed economies should expand their role in the value chain by extending their products with services so they do not have to compete solely on cost [53,54]. Neely et al. [55] published a study that shows five fundamental developments: *“(1) the shift from a world of products to a world including solutions, (2) outputs to outcomes, (3) transactions to relationships, (3) suppliers to network partners, and (5) elements to ecosystems.”* The result are so called Product-Service Systems (PSS), a framework describing the integrated development, realization and offering of specific product-service bundles as a solution for the customer [9].

This is fully in line with the idea of Smart Manufacturing, where CPS provide the solution for a certain problem through the outcome of their application. Instead of one-off sales transactions, CPS build relationships with other systems and their environment. For example, access to lifecycle (usage) data may allow the manufacturers to improve their processes and offer additional services around their core product, as in the case of aircraft video surveillance. As a result, suppliers, customers and other partners become part of a networked ecosystem around the CPS. Gorldt et al. [56] have coined the term “Cyber-physical Product-Service System” (CPSS) for the integration of the PSS concept and Smart Manufacturing. A manufacturing enterprise however that changes from the fabrication of products to offering CPSS solutions and transforms its supplier base into an ecosystem of network partners will have to analyze and adapt various elements of its BM to stay profitable and competitive. According to Osterwalder and Pigneur [57], these elements comprise not only the new value proposition, but also different customer segments and relationships, distribution channels, key resources, activities and relationship, as well as a changed cost structure and revenue streams. This creates several challenges for the company (see Fig. 8.).

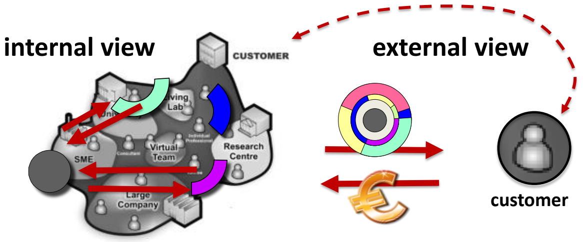


Fig. 8. Business Model Innovation

From an internal viewpoint on how to develop and realize the CPSS. How are risks and opportunities distributed among the network partners? What is the innovation effort compared to amortization time? But as well from an external viewpoint on the CPSS offer. What is the added value for the customer and the value of data? Who is paying for which results?

The task for manufacturing enterprises is to integrate the new and unknown value proposition of a CPSS and the associated collaborative arrangements into their BM without experience in this field. Building networks with unconventional business partners is difficult and can bring incalculable risks. Innovative technologies have to be utilized for service provision and to develop closer relationships to the customer. New stakeholders in the ecosystem affect the cost structure and require new kinds of revenue models, which are currently not elaborated in manufacturing industries. Wiesner et al. [58] have developed an approach, based on methods like the "Blue Ocean Strategy" [59] and the BM Canvas [57], which supports manufacturing enterprises in this transition.

5. Conclusions

In this paper, the fourth industrial revolution, called 'Industrie 4.0' (Germany/EU) and Smart Manufacturing (USA) has been in the focus. The momentum and traction both initiatives (and similar ones in several other countries) gained in recent years highlights the rapid, paradigm shifting change the manufacturing industry and manufacturing research are undergoing today. I4.0 and Smart Manufacturing describe the transition towards a heavily data focused, supply network wide integration of information and communication technology and increased automation, while keeping the human in the loop. The goals are manifold and diverse, with energy saving, sustainability (social, economic and environmental), agility/resilience, as well as quality and efficiency improvements being in the center.

Several application scenarios were presented that have highlighted the wide scope of Smart Manufacturing. One application case focused on a cyber-physical logistics system for intralogistics that could reduce Kanban cycles and distances. The second one highlighted human robot interaction on the shop floor and how I4.0 can ensure the safety of the human worker and co-bot working together in close proximity. The third use case gave insights in the application of video streams and operational data from an aircraft cabin surveillance system to offer new and enhanced archiving and analysis services through an innovative business model. The three use cases from different domains present a small selection of the diverse applications and challenges I4.0 and Smart Manufacturing have to deal with on the one hand, and what huge potential lies in these new initiatives.

After the application cases were presented, current and future research issues were derived and illustrated. Three main categories, technical, methodological and business case challenges were chosen to structure the different research issues. It has to be noted, that while the list of research issues is long already, the issues identified and discussed are rather high level and the list does not claim to be comprehensive. The research issues selected for presentation in this paper were mainly based on the three use cases. As Smart Manufacturing and I4.0 are such overarching, paradigm shifting initiatives, there are many more research issues relevant today and most likely even more tomorrow (in the future). The more I4.0 and Smart Manufacturing are accepted and adopted by industry and academia, the more different fields and research areas discover the potential of their work within the greater system, the more traction Smart manufacturing and I4.0 will get and the more research issues will surface.

While there are already successful testbeds available, I4.0 and Smart Manufacturing are still in their early stages. Given the attention and available grants from funding agencies and the severe interest from industry (both large corporations and SMEs), it can be expected that the near future will present rapid developments in this area. Due to its interdisciplinary nature, advances in basic research fields may find their way to industrial application more rapidly than it was the case in past years. This may be a chance for researchers who have not had much interaction with applied research in their field to collaborate with researchers of supplementing fields and industry to see their work being used in real life applications.

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