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Review

Ten Years of Industrie 4.0

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Abstract: A decade after its introduction, Industrie 4.0 has been established globally as the dominant paradigm for the digital transformation of the manufacturing industry. Amalgamating research-based results and practical experience from the German industry, this contribution reviews the progress made in implementing Industrie 4.0 and identifies future fields of action from a technological and application-oriented perspective. Putting the human in the center, Industrie 4.0 is the basis for data-based value creation, innovative business models, and agile forms of organization. Today, in the German manufacturing industry, the Internet of Things and cyber–physical production systems are a reality in newly built factories, and the connectivity of machinery has been significantly increased in existing factories. Now, the trends of industrial AI, edge computing up to the edge cloud, 5G in the factory, team robotics, autonomous intralogistics systems, and trustworthy data infrastructures must be leveraged to strengthen resilience, sovereignty, semantic interoperability, and sustainability. This enables the creation of digital innovation ecosystems that ensure long-term adaptability in a volatile economic and geopolitical environment. In sum, this review represents a comprehensive assessment of the status quo and identifies what is needed in the future to reap the rewards of the groundwork done in the first ten years of Industrie 4.0.

Keywords: Industrie 4.0; intelligent manufacturing; smart factories; industrial artificial intelligence; digital twins; zero-defect manufacturing; digital ecosystems

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1. Introduction

Our initial article, *Industrie 4.0: With the Internet of Things Towards the 4th Industrial Revolution*, was published in German on 1 April 2011 in cooperation with Wolf-Dieter Lukas, shortly before the opening of the Hanover Fair took place [1]. At this time, under the impact of the global financial crisis, we aimed to make the German economy more resilient and competitive by strengthening adaptability and resource efficiency.

This review discusses, from a conceptual and technological perspective, which elements of Industrie 4.0 have been fully implemented ten years after it had been drafted by us and which technological trends are now required for deepening the digital transformation of the manufacturing sectors.

2. Industrie 4.0: From a Conceptual Framework to an International Brand

Our main idea was to merge real and virtual spaces in so-called cyber–physical production systems, building on progress that German industry had already made with the lighthouse projects on the Internet of Things (IoT) and the Internet of Services (IoS) [2]. This was technologically interesting but would only have had an impact in specialist circles, not in practical implementation. Our term 'Industrie 4.0' got to the heart of the subject and attracted significant attention.

We received strong political support. As early as 3 April 2011, German Chancellor Angela Merkel spontaneously picked up on the new brand 'Industrie 4.0' in her opening speech at the Hanover Fair. However, also the business community, trade unions, and, very importantly, representatives of other industrialized countries recognized the magnitude of this concept. Our initial focus on the manufacturing sector was of considerable importance. It was widely accepted that economies with a strong industrial backbone such as Germany recovered faster and better from the global financial and economic crisis.

The term 'Industrie 4.0' has spread virally and is now associated with Germany all over the world, similar to 'kindergarten' and 'autobahn'. Industrie 4.0 is an export hit that has received attention and recognition in business, science, and politics around the globe. For the first time in the high-tech world, we have once again been able to establish an innovative concept from Germany internationally, after they had mostly come from North America or Asia for many years. Industrie 4.0 has made Europe the most innovative factory supplier of the world. There does not exist any 'smart factory' anywhere in the world where a large number of software and hardware components does not come from European companies. However, for the next decade of Industrie 4.0, the continuing support of stakeholders and international cooperation are required to reap the rewards of the groundwork done in the first ten years of Industrie 4.0. This also encapsulates leveraging the six key trends: industrial AI, edge computing up to the edge cloud, 5G in the factory, team robotics, autonomous intralogistics systems, and trustworthy data infrastructures.

3. Basic Prerequisite and Success Factor: Putting the Human at the Center

The networking and connectivity of people, intelligent objects and machines, the use of service-oriented architectures, and the composition of services and data from different sources to form new business processes is opening opportunities. Industrie 4.0 does not lead to factories empty of people. On the contrary, employees are supported by physical and cognitive assistance systems realized by collaborative robots (Cobots) and software agents (Softbots), which support the humans in complex manufacturing tasks (see Figure 1).

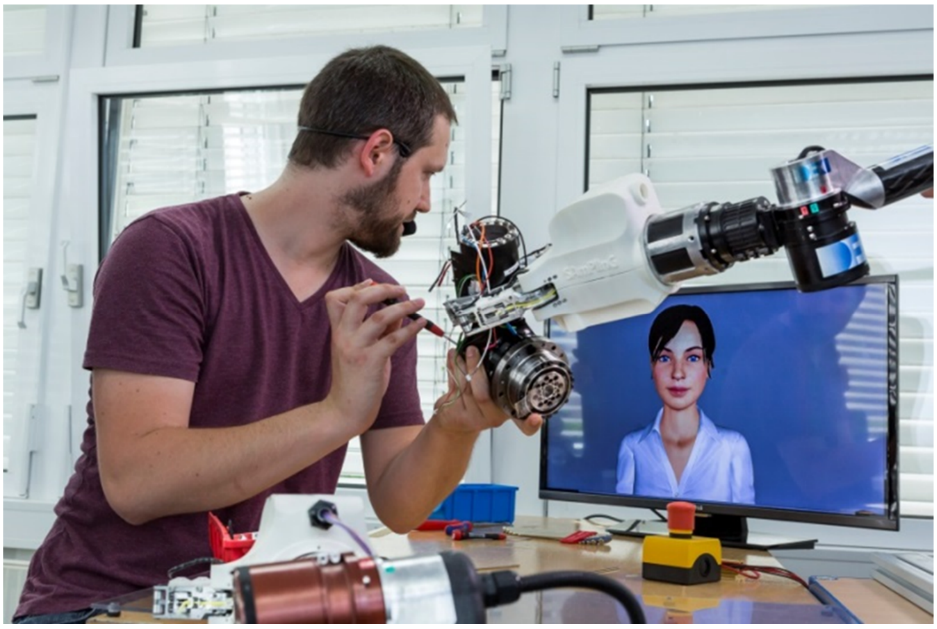

Figure 1. A Cobot and a Softbot helping a human worker (Source: DFKI).

Industrie 4.0 is the basis for data-based value creation, innovative business models, and agile forms of organization, but also for new solutions in areas such as energy, health, and mobility.

This vision is compelling because it puts people in the center, promising significant progress for the economy and society at large. In economic terms, it initially involved a shift from traditional automation with predetermined outcomes to learning and self-adapting machines and environments that respond in real time to changes in customer demand, as well as to unexpected disruptions. This is accompanied by a move from mass production to mass customization, i.e., the competitively priced production of individualized, tailor-made artefacts [3].

In social terms, the focus was set on implementing social partnerships for Industrie 4.0. Therefore, trade unions were closely involved in the entire process and contributed constructively. Focus points were set on the promise of better and more meaningful human–machine cooperation without the fear of losing control, the creation of jobs through 'nearshoring', and the inclusion of older and disabled people, supported by physical and cognitive worker assistance systems.

Ecologically, resource and energy efficiency has been a central goal from the outset: Industrie 4.0 has the potential to establish a circular economy that decouples economic growth from resource consumption. Sustainability through upcycling and the resilient factory have been two of the use cases proposed in our recommendations [3].

4. Key Challenge: Managing the Digital Transformation of the Manufacturing Industry

The success of Industrie 4.0 is closely interrelated with the broad support of the mainstays of society. The wide-scale roll-out of Industrie 4.0 during the last ten years was based on the effective cooperation of trade unions, industry, politics, and academia, institutionalizing their collaboration via an appropriate digital and organizational platform. Industrie 4.0 has set standards for how quickly a concept that initially emerged in cutting-edge research can develop out of companies and industry associations and, with the active accompaniment and support of the trade unions, can lead Germany to success as a location for business and innovation. Today, Industrie 4.0 is at the top of the agenda for federal policy—in the past ten years, more than 1000 project consortia, 10,000 conferences, and 100,000 publications have dealt with its technical and scientific implementation (see wiso-net.de in www.genios.de, accessed on 4 June 2022).

The Internet of Things (IoT) and cyber–physical systems are now a reality in newly built factories [4]. At the same time, in existing factories, the connectivity between machines, tools, workpieces, and skilled workers was improved, relying on various migration and bridging technologies for Industrie 4.0 [4]. Retrofitting—the digital upgrade with new low-cost sensors and their wireless connectivity—is steadily advancing. More and more production steps can be monitored in real time through multi-sensor fusion—for example, for quality control. The emerging product controls its own production via its digital twin. As in a marketplace, it selects the production services that match the customer's requirements, relying on the digital twins of the networked production facilities.

Today, there are a number of 'smart factories' that implement the basic principles of Industrie 4.0 [5,6], including 'Plug & Produce' and the virtual commissioning of new plant components relying on various types of digital twins (e.g., product twins, process twins, or machining twins), as well as cycle-independent matrix production architectures or multi-agent architectures, with heterarchical and modular holonic control regimes, with configurable production cells and short set-up and changeover times even for the smallest batch sizes, and with a high degree of product individualization. This also holds for variable intralogistics combined with real-time production planning, as well as for location-based services for all workers, operating resources, and the products being created. Factory floor positioning has been greatly improved for mobile systems such as autonomous forklifts using AI-based visual SLAM (Simultaneous Localization and Mapping) techniques. GPU computing for the massively parallel execution of neural networks on very powerful graphics cards has significantly improved the necessary recognition of landmarks to enable the free and precise navigation of mobile robots.

After the experience of the COVID-19 pandemic, we need to develop solutions to avoid disruptions in supply chains or production stoppage due to short-term staff shortages [7]. Home-office technologies are hardly helpful in this regard. So-called 'home workbenches' that enable the mobile control, maintenance, and repair of factory equipment as software solutions with remote access to cyber–physical systems through tele-operation with physical avatars are needed instead.

5. What Is Next? New Megatrends for the Next Decade of Industrie 4.0

What is next? We must continue to drive semantic interoperability and international collaboration in open ecosystems. Six new megatrends (see illustration in Figure 2) will decisively influence the development of the next 10 years: industrial AI, edge computing up to the edge cloud, 5G in the factory, team robotics, autonomous intralogistics systems, and trustworthy data infrastructures.

Industrial AI will enable a second wave of digitalization of production. The first level, making all production and supply chain data available digitally and mobile via cloud systems, is largely achieved. These data can now be analyzed by AI systems in real time and interpreted in context even on the edge (e.g., signal-based machine learning with time delay on sensors [8]) so that they can be actively used for new value chains and business models.

With digital training data for machine learning systems, AI systems can be used not only for predictive maintenance, which is already widespread, but increasingly for incremental quality control, mostly via video sensors. Thus, the next phase of Industrie 4.0 will aim for AI-based zero-defect production (see Section 6). Self-learning capability and modular long-term autonomy rather than simple automation will characterize the new generation of 'smart factories' and, in addition to extreme flexibility, guarantee extremely robust production, high occupational safety, energy efficiency, and a high degree of resource conservation. A capability-oriented production architecture ensures expandability and mutability at the next level of Industrie 4.0 to respond quickly to volatility in the markets.

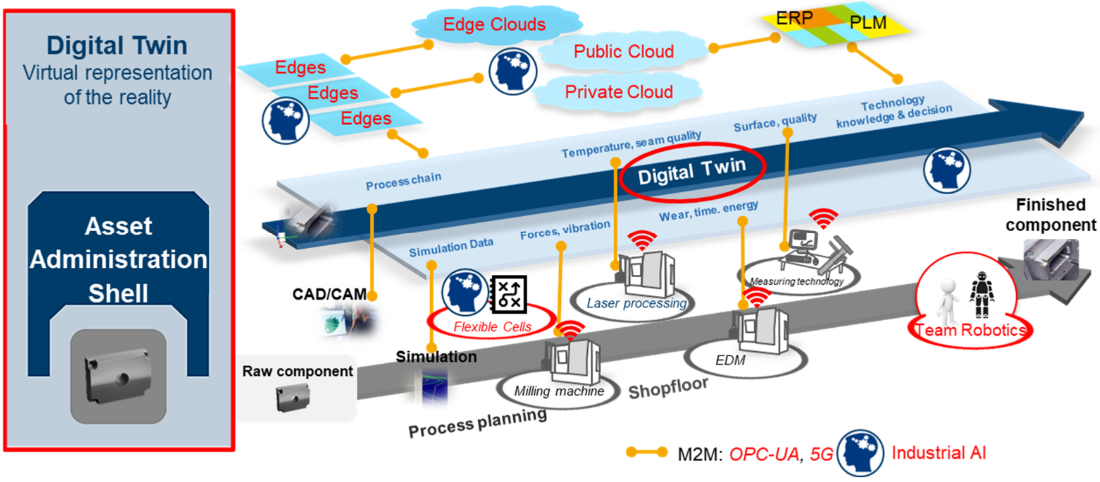

Figure 2. Megatrends for the next level of Industrie 4.0 (own illustration).

In 5G campus networks, edge devices can exploit the high bandwidth and low latency guaranteed with 5G to build a local edge cloud that can then meet real-time requirements on the factory floor. Mobile and real-time teleoperation, combined with multimodal sensor fusion, will also enable remote maintenance, repair, and installation.

In 'smart factories', intra-logistic planning and production planning are coordinated in real time, highly flexibly: mobile robots, factory drones, and driverless transport systems ensure that the parts and tools needed for the next planned production step are available just in time, at the right production island (see Figure 3).

Figure 3. Industrie 4.0 in a smart factory (Source: SmartFactory ^{KL} and DFKI IFS).

Production planning is revolutionized by a new service-oriented production architecture: the specification of the digital twin of the emerging product tries to find production capabilities that will transform the semi-finished product into its final state. Thus, digital twins become active agents in a multi-agent architecture, where the required skills of workers and machines are coordinated in real time. This enables the specification of products by semantic matchmaking.

Hybrid teams of workers and collaborative robots with different skill sets enable a new form of team robotics that focuses on human–machine interaction led by skilled human personnel. To solve complex manufacturing tasks, they are working hand-in-hand with robots as a team.

Data infrastructures must integrate industry requirements for data sovereignty, decentralization in heterogeneous multi-cloud systems, and edge support. After the first decade of Industrie 4.0, factories digitally record, transmit, and store all production and machine data as sensors capture all relevant process data on edge devices. This is a first step towards higher productivity and more transparency of manufacturing processes. However, the interpretation of these data sources still requires manual data analysis by human experts using various digital data visualization and data analysis tools. Due to the massive amount of data provided in real time in an Industrie 4.0 factory, human data analysts will soon reach their limits.

An important goal for the next decade of Industrie 4.0 is therefore the automatic interpretation of industrial data based on artificial intelligence (AI). It is an enabler, e.g., for zero-defect production, and it is the decisive innovation to ensure that the superior quality of our products remains a unique selling point compared to similar products from the US or China. This requires the implementation of the entire cognition cycle from perceiving over understanding to acting, with all phases supported by various forms of machine learning relying on digital mass data from cloud and edge platforms [9] (p. 68). In addition, we must enable industrial AI systems to learn new knowledge not only autonomously from empirical data but also from being taught by human experts in interactive human–machine conversations, or from machine understanding of relevant technical documents.

6. Strategic Field of Action I: Towards Zero-Defect Manufacturing Based on Industrial AI

Zero-defect manufacturing can create a competitive advantage over 'low-wage and low-tech countries', since most consumers prefer high-quality, reliable, and sustainable products, even if they come with a somewhat higher price. Detecting anomalies and defects in the production process too late causes immense costs and has a negative impact on sustainability and productivity, as it leads to an enormous waste of time, energy, and material. It is therefore of the utmost importance to detect, explain, and eliminate such errors as early as possible—ideally immediately when they occur—by taking appropriate measures.

Typical sources of errors are the incorrect actions of a worker or a robot, or the incorrect interaction of workers and robots in the process. AI-based plan recognition, intention, and interaction recognition modules use video streams, wearable sensors, and IoT devices for incremental error detection. Thus, instead of one big loop for error correction after the traditional final quality check of the product, the next generation of systems consists of many small quality management loops. This eliminates the need for final inspection and partial disassembly of the already finished but faulty product for repair (see Figure 4).

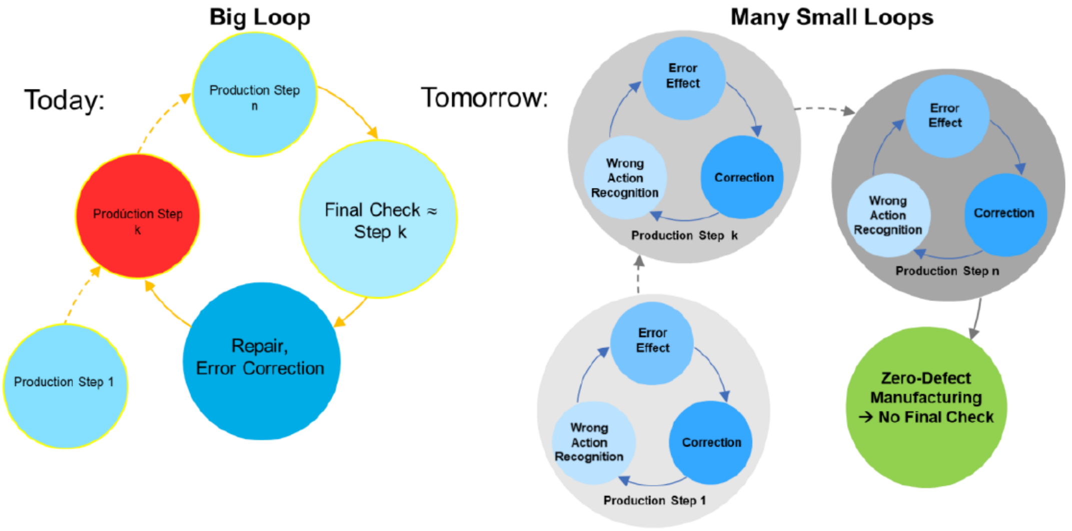

Figure 4. AI-based quality management with incremental error recognition (own illustration).

Of course, the earliest time to reliably detect an incorrect action, interaction, or out-of-control state is the moment it emerges. For this purpose, relevant quality-, task-, and interaction-specific parameters and constraints are continuously evaluated by AI-based methods during incremental real-time checks. These AI-based methods combine statistical deep learning methods on diverse sensor data streams with semantic models encoded in digital twins and symbolic reasoning. As real recorded data for training models are often not available, synthetic data must be generated, e.g., through accurate simulations involving digital twins.

Detected errors must be immediately reported to the responsible workers with a comprehensive explanation and a checklist to avoid them in the future and on how to proceed further if the error occurs. This requires intelligent user interfaces with massively multimodal explanation capabilities for human workers and production experts.

Thus, not only deep learning but also deep understanding by AI systems need to be strengthened in the next decade of Industrie 4.0 to allow for the implementation of explainable, more robust, and trustworthy systems (see [10]). We must include novel architectures beyond current deep learning, capturing causality and meta-learning to enable more powerful forms of compositional generalization. On the one hand, current machine learning systems lack the ability to leverage the invariances included in causal relations, which would be needed to boost their generalizability, robustness, and explainability [11].

Current causal inference methods, on the other hand, lack the ability to scale up to higher-dimensional settings, where current machine learning systems excel. Recently, a shift in research direction and new tools are opening the door to the development of novel architectures for addressing more sophisticated tasks, capturing causality and systematic generalization in error diagnosis, repair planning, and recovery. We predict that meta-learning, compositional generalization, and representation learning are needed for the next generation of industrial AI systems during the next decade of Industrie 4.0.

7. Strategic Field of Action II: Shaping Digital Ecosystems

In 2019, experts from the 'Platform Industrie 4.0' updated the vision of Industrie 4.0 for 2030 with the headline 'Shaping digital ecosystems globally' [12]. We must continue to drive semantic interoperability and international collaboration in open ecosystems, which permits plurality, diversity, flexibility, and a corporate culture of sharing success with business partners. We strive for a sustainable economy where economic growth is decoupled from resource consumption. We also strive for sovereignty—self-determination—at all levels. In a networked economy, self-determination means, above all, the freedom to select the technology of choice, the business partner of choice, the location of choice—especially the place where data are stored and processed in accordance with the legal system in force there. Against the background of recent developments and geopolitical challenges and the resulting shortages and bottlenecks in supply chains, with significant effects on industrial value creation, in particular, rethinking the security and resilience of supply becomes more important. Diversified supply chains and the ability to redesign value chains on demand seamlessly are fundamental in this regard. In the next phase of Industrie 4.0, companies must therefore exploit the advantages of digital factories and distributed modular production architectures to build trustworthy and reliable industrial digital ecosystems [13,14].

An additional challenge is business model innovation: understanding the customers' processes and extracting enterprise value from customer value. The value proposition in a digital economy is smart services [15]: individualized product–service bundles on demand, with superior user experience and low effort in switching to alternative business partners. The supporting value-creating architecture is illustrated in Figure 5, demonstrating the need to rethink and reengineer business processes as well as workplaces exploiting the power of AI [16] and replacing manual or cognitive routine tasks by autonomous systems. For all activities of the value chain, dynamic business networks must be established with dedicated orchestration models and governance. Obviously, a secure and trustworthy data supply chain and frictionless interoperability in technological and business terms are fundamental for success (see Figure 5).

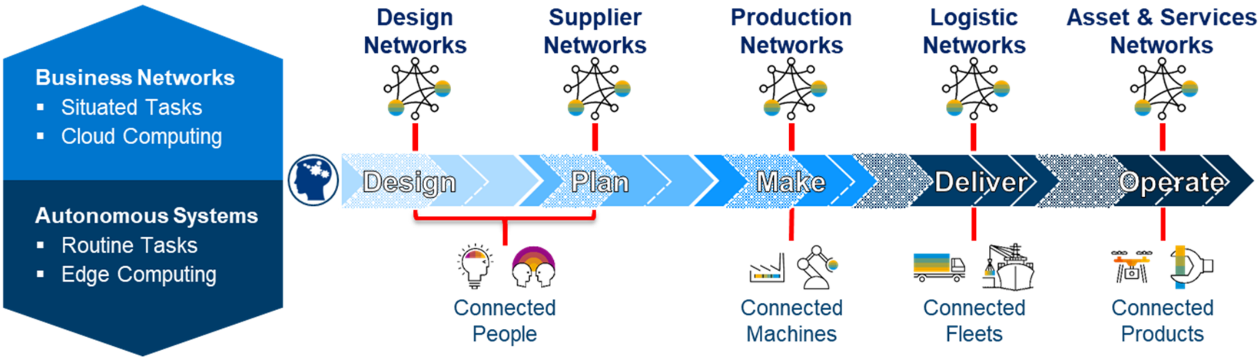

Figure 5. The digital enterprise (own illustration).

Digital enterprises have higher capabilities to operate in digital value creation network models. Within these decentralized networks of firms, governed by reciprocity and shared success, collaborative and coordinated elements for joint value creation are balanced to pursue the joint development of platform-oriented business models [17].

Digital ecosystems are the base layer and are dependent on a digital economy because many of the ecosystem members operate in different countries under different regulations and legal conditions [18,19]. This is why international cooperation on standards and secure data exchange across borders are of the utmost importance, particularly to guarantee sovereignty in an interconnected digital economy.

Many efforts have been undertaken in European initiatives such as Gaia-X in building a data infrastructure allowing for the sovereign exchange of data supported by an architecture for data spaces comprising technological standards, guidelines, and rules [20].

8. Outlook: Industrie 4.0 Has Still a Long Way to Go

For the next decade of Industrie 4.0, we even need to go beyond today's cloud and multi-cloud systems, since advanced distributed production systems need sky computing as a cloud of clouds [21]. Today's cloud market is fragmented, with many proprietary services running on proprietary hardware accelerators (e.g., TPUs, GPUs) and offering incompatible APIs. Based on the compatibility and intercloud layers of the emerging sky computing platforms, APIs can be used without changes, allowing applications to run on multiple clouds transparently. Such platforms are urgently needed if we want to realize the vision of full circular economy loops in distributed solutions for Industrie 4.0 with thousands of data providers and data consumers.

Many of the challenges of Industrie 4.0 are transnational and require continued international cooperation. We must simultaneously preserve our digital sovereignty while sharing our knowledge, experience, and best practices internationally. Other countries will favor different solutions in some cases, due to different political systems or culturally different approaches to problem solving. Nevertheless, our answer can only be self-determination and open collaboration based on our own values. For example, we presented the first comprehensive AI standardization roadmap in December 2020 [22].

We must not reduce our efforts in research and innovation for the next phase of this fourth industrial revolution. For the second wave of industrial digitalization, a major investment in industrial AI is required. Digital twins, which are already of the utmost importance in almost all sectors of industry, will become even more decisive. The semantic interoperability of software and hardware components plays a crucial role, especially to ensure international market access for German SMEs and startups, but also to safeguard Europe's technological sovereignty.

Standards, norms, and certificates are decisive drivers for interoperable solutions. The Asset Administration Shell (AAS), developed by the Platform Industrie 4.0 [23], is a promising attempt in this regard. Semantic interoperability also contributes to strengthening ecological sustainability, e.g., an AAS-based demonstrator, developed by Platform Industrie 4.0 and CESMI, creates transparency regarding greenhouse gas emissions across the value chain [24]. These factors deserve specific attention in the future.

In the next decade of Industrie 4.0, the continuing support of policymakers, trade unions, and civil society is needed, in addition to substantial funding for research and innovation. Only in this case can the economic, social, and ecological fruits of the significant investments in the first decade of the fourth industrial revolution emanating from Germany be harvested.

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