DIN and DKE ROADMAP

German Standardization Roadmap Industrie 4.0

Version 4

STANDARDIZATION
COUNCIL
INDUSTRIE 4.0

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Foreword

Dear Reader

Prof. Dr. Dieter Wegener,
Chair SCI 4.0 Advisory Board
Speaker DKE Vice President

Six years ago the first edition of the Standardization Roadmap Industrie 4.0 had its premiere. A lot has happened since then. Over the past six years the term Industrie 4.0 has developed from a catchword to a tried and tested approach and now describes a completely new level of production as well as the organization and control of the entire added value chain. Technically, Industrie 4.0 represents the fusion of IT (Information Technology) and OT (Operational Technology).

This leads to a significant overlapping of previously separate areas of standardization. Issues, requirements and working methods that were previously relevant to the information and communication technology sector, for example, now also affect mechanical engineering and the electrical industry to an even greater extent.

As a consequence it is now time to think some more about Industrie 4.0: What will a global digital value added system look like? How can we identify and implement the right normative framework for this? The current Mission Statement 2030 of the Platform Industrie 4.0 already formulates a holistic approach to the design of digital ecosystems and realigns the development of Industrie 4.0. Three central strategic fields of action are decisive here: **(1)** Autonomy, **(2)** interoperability and **(3)** sustainability. The "Standardization Council Industrie 4.0" (SCI 4.0) has taken up this idea and has set itself the goal of promoting the combination of these approaches together with DIN and DKE by formulating recommendations for standardization.

With this "Version 4" of the Roadmap we want to set down a vision for Industrie 4.0: the achievement of interoperability. By this we mean that machines in networked digital ecosystems communicate with each other in an interoperable manner. Only a high degree of interoperability ensures networking across company and industry boundaries. This requires standards and integration, a uniform regulatory framework, decentralized systems and artificial intelligence.

As Speaker of the Advisory Board I am pleased to see that the Standardization Council Industrie 4.0 plays an important and concerted role in identifying these framework conditions. With this Standardization Roadmap Industrie 4.0 as a "*living document*", ambitious, feasible recommendations for action are developed and addressed to all actors. This also includes the international dimension, i.e. the international initiation and coordination of suitable standards.

There is positive news to report on the implementation of the recommendations for action so far. For example, the activities of the "ISO/IEC Joint Working Group 21" (ISO/IEC/JWG21) on the harmonization of Industrie 4.0 reference models are nearing completion with the final Technical Report. The newest development is the adoption of the standards proposal for the administration shell by IEC/TC 65, which was adopted by a clear majority This sets the course for making the administration shell the central "*USB standard*" for digital ecosystems. These are just a few prominent examples of the success story.

Of course, in the current version of the Roadmap we also devote ourselves to new topics that were not considered in the past. Most recently, it was the diversity of existing and potential areas of application and the current focus of politics, science and users on the topic of artificial intelligence (AI) that raised high expectations for its use in Industrie 4.0. Novel processes and design possibilities through AI automatically also raise questions regarding common standards and guidelines, which often, for example in functional safety and occupational health and safety, refer to planned and partly certified procedures and systems and do not yet know the answer to the use of dynamic decision processes in AI systems.

This chapter presents a possible "*vertical*" classification of the impact of AI in industrial production – i.e. Industrie 4.0 – and attempts to provide the still open answers in the form of recommendations for action.

Humans and their knowledge still play the main role in drawing up this standardization roadmap. I am always fascinated by the high degree of participation and the willingness of the experts to devote themselves to this "*project Standardization Roadmap*". Without the willingness to contribute your knowledge and commitment, we would not be able to celebrate our "Version 4" today. With this in mind, I would like to take this opportunity, also on behalf of the SCI 4.0 Advisory Board, to thank all authors and participants for their tireless efforts.

The task now is to implement the recommendations for action and prepare the ground for the next edition today.

I wish all readers an exciting read.

Your
Prof. Dr. Dieter Wegener
Chair SCI 4.0 Advisory Board
DKE Vice President
Speaker ZVEI-Führungskreis Industrie 4.0

Summary

In the tradition of the previous standardization roadmaps, the present edition shows, in addition to the current standardization status of Industrie 4.0, in particular the standardization gaps and normative inconsistencies which need to be revised or adapted as quickly as possible. This results in recommendations for action and application formulated at the end of each chapter.

Since the publication of Version 3 two years ago, important standardization projects have been initiated at national level and subsequently implemented at international level.

Design of a metalanguage for reference architecture models

The role of the human being is first of all that of the developer and user who controls and monitors the running processes and, if necessary, intervenes to control them. The interaction and communication between the factories and their machines, however, goes beyond the boundaries of the factory and company. In this way, companies from different sectors, such as suppliers, logistics companies and manufacturers, are networked together in a value-added system. Very different systems must communicate and interact with each other. For this to be successful, interfaces need to be harmonized. This in turn presupposes that the design of these interfaces is based on standards and specifications that are as internationally coordinated as possible.

A reference architecture model, i.e. a uniform conceptual and methodological structure, forms a basis for ensuring that the experts involved in the various disciplines master this complexity and speak a common language. It creates a common structure for the uniform description and specification of concrete system architectures. The reference architecture model Industrie 4.0 – RAMI 4.0 – developed in Germany represents such a model. This model has now been successfully introduced into the international standards landscape and has been published as IEC PAS 63088.

Description of the structure of an administration shell and its sub-models

The next major step is to define suitable data structures for the exchange of data and their defined meaning. This standardized exchange of data and their defined meanings is called semantic interoperability. The concept of the administration shell was developed in Germany for this exchange [1]. Hardware and software components in production, ranging from the production system itself to the machine or station to the individual subassembly within a machine, become Industrie 4.0-capable by fulfilling these characteristics. These characteristics include the communication capability of real objects and the associated data and functions. The model thus describes the requirements for Industrie 4.0-compliant communication between the individual hardware and software components in production. In order to help the structure of the administration shell defined in Germany achieve a breakthrough in international standardization, the concept was pre-agreed with partners from France, Italy and China, among others, under the coordination of SCI 4.0.

A first important step has been taken with the adoption of the standardization proposal IEC 63278-1 ED1 *"Asset administration shell for industrial applications – Part 1: Administra-*

tion shell structure" within IEC/TC 65. This sets the course for making the administration shell the central "*USB standard*" for digital ecosystems. Work on the project began in February 2020.

Germany takes on responsibility for Industrie 4.0 standardization

With the GoGlobal Industrie 4.0 funding project, the German Federal Ministry for Economic Affairs and Energy (BMWi) has been supporting the global harmonization of national Industrie 4.0-concepts through the SCI 4.0 since December 2017. In this way, the recommendations for action compiled in the standardization roadmap can be formulated as recommendations for action in the Industrie 4.0 standardization roadmap. In general, the cooperating countries are actively represented within the international standards organizations, such that timely and consensual cooperation plays a significant part in achieving the desired goal. The stabilization of the concepts through the bi- and trilateral channels for discussion is essential from a German perspective in order to synchronize this work with the relevant international standards bodies. More specifically, bilateral cooperation channels with China, Japan, South Korea and the USA have been opened and are actively involved in the harmonization process. In the European context, a trilateral cooperation between France, Italy and Germany has been consolidated, which also works towards the wider European Industrie 4.0 community and paves the way for a common European path.

The respective cooperations at international level address the relevant ISO and IEC committees and, in turn, require a high degree of cooperation and transparency in the design of joint processes and results. This approach is in line with the internationalization strategy of the Platform Industrie 4.0. For example, the Standardization Roadmap Industrie 4.0 defines recommendations for standards work, which are coordinated for implementation in consultation with the relevant working groups in DIN and DKE.

In other words, it is part of the mandate of the Standardization Council, together with experts and the international partner countries, to develop suitable solutions and coordinate them with IEC and ISO in a joint, harmonized approach. Following these approaches, and in order to ensure better and more efficient cooperation between the individual disciplines, two further bodies have recently been set up which Germany has strongly supported and promoted: the establishment of the IEC System Committee "Smart Manufacturing" (IEC SyC SM) and the working group IEC/TC 65/WG 24, in which the aspects relating to the administration shell will be introduced in future.

In all cooperations, collaboration beyond the previous topics is planned. The profound change is taking place step-by-step in the change of the organizational and value creation structures of the companies. The value creation is shifting to platforms or services through the evaluation of data. The upcoming breakthrough of artificial intelligence (AI) technologies expands the possibilities to analyse data and supervise production processes.

These examples show that the first implementations of central recommendations for action are already starting this year and will be intensified in the future. The Roadmap will also be regularly updated to reflect new findings, for example as gained in research projects or work within standards bodies. We would therefore like to encourage and motivate you to actively participate in this process.

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1 Introduction

One thing is certain: the success of the future project Industrie 4.0 will require an unprecedented degree of system integration across domain borders, hierarchy borders and life cycle phases. This can only be achieved on the basis of consensus-based standards and specifications. With the Standardization Roadmap Industrie 4.0 now published, the Standardization Council Industrie 4.0 (SCI 4.0), together with DIN and DKE, has presented a strategic and technically oriented document in which experts from industry, research, science and politics, across disciplines, describe the current development status of Industrie 4.0, outline the requirements for standards, specifications and industry standards, and provide impetus for successful implementation.

To ensure successful implementation, SCI 4.0 brings together stakeholders in Germany and, together with experts from industry, research and the standards organizations DIN and DKE, develops a consolidated national basic position (national harmonization) which is reflected in the recommendations for action and application formulated here. At the end of the process, the goal is to initiate digital production standards and to coordinate them first nationally and then internationally.

The recommendations for action described in Chapter 2 to 4 are closely related to the German Standardization Strategy presented in Chapter 1.1 and represent an important reference for the daily work of numerous standards experts.

1.1 German Standardization Strategy

In the coming years this joint strategy will form the basis for the work of the German standards organizations DIN and DKE. Other German issuers of technical rules and platforms actively support the German Standardization Strategy. The German Standardization Strategy [2] is in line with the regulatory framework and principles of standardization, as specified, for instance, in the WTO criteria, the European Regulation on Standardization, the Standards Agreement between DIN and the Federal Republic of Germany, and DIN's principles of standards work.

DIN and DKE are recognized by German policymakers, industry and society as institutions that contribute to industry's global competitiveness, and specifically to Germany's global competitiveness, through standardization. Within the framework of the German Standardization Strategy, both German standards organizations emphasize the international relevance and recognition of ISO and IEC and strengthen these two international institutions.

In addition, both standards organizations see themselves as a global moderation platform for standardization, organizing standardization topics and coordinating cooperation across the borders of their own organizations, including cooperation with fora and consortia and other standards organizations. Joint subject-specific steering committees at DIN and DKE are in their role catalysts for digital transformation in the standards world.

A further supporting pillar of standardization is the industry. Companies commit themselves over the long term competently, and with their technology experts strengthen national, European and international standardization.

At executive and management level standardization is used as a strategic tool to achieve company targets; participation in standards committtees is promoted and commended.

The Standardization Strategy also focuses on the installation of efficient processes and instruments, as well as on avoiding delays in progress. However, in certain areas, a longer standardization process may delay progress. Dynamic future markets such as Industrie 4.0 or Information and Communication Technology (ICT) therefore require forms of publication that can be developed and made available to the general public within a short period of time. Attempts are already being made to counteract this through the use of application rules, guidelines and specifications. Ultimately, however, these forms of publication also require a certain consistency and coordination of their content in order to help prepare national standards work in a consolidated manner. [**RE 1.1-1**]

This possibility is offered by the following forms of publication, which help to prepare the national standards work:
→ DIN SPEC
→ VDE Application guide
→ VDI Guidelines
→ VDMA Specifications

Various research projects deal with central questions concerning Industrie 4.0 and are related to standardization. For example, DIN and DKE are accompanying a number of projects supported by the Federal Ministry for Economic Affairs and Energy (BMWi) and of Education and Research (BMBF) as partners in the development of standards. For the success of Industrie 4.0 and for the implementation of recommendations for action, corresponding funding programmes are absolutely necessary.

WIPANO – Knowledge and Technology Transfer through Patents and Standards
The technology funding programme "WIPANO – Knowledge and Technology Transfer through Patents and Standards" of the Federal Ministry of Economics and Energy (BMWi) will enter the next round starting from 2020. The programme contains new elements specifically supporting small and medium-sized enterprises (SMEs). It will also facilitate participation in patent and standardization funding in order to reach even more SMEs in the future. With the new funding focus "Enterprise – Standardization", the BMWi is implementing a further measure from its industrial strategy 2030. SMEs and freelancers are to be sensitized to the importance of standards work and won over for cooperation in this work.

DIN-Connect
With DIN Connect, DIN and DKE launched a programme in 2016 to promote innovation. In particular, DIN and DKE support projects which have the development of specifications as a goal. The programme is aimed primarily at start-ups and SMEs, with the aim of transferring innovations to the market with the help of standards and specifications.

This Standardization Roadmap will also be regularly updated to reflect new findings, for example as gained in research projects or work within standards bodies, and with the greater involvement of small and medium-sized enterprises.

1.1.1 Recommendation for action and application

1.1-1 Standards and specifications should preferably be developed and published by international organizations in order to achieve worldwide acceptance. National forms of publication may be appropriate in the sense of pre-standards to support the formation of national opinion. Possible forms of publication include the DIN SPEC, VDE application rules, VDI Guidelines, VDMA Specifications and more. If national forms of publication are envisaged, care must be taken to ensure that the license and usage conditions allow for smooth internationalization at a later date.

1.2 Significance of the digitalization of standardization

Digital transformation is affecting not only industry and its products, services and processes, but also the digitalization of standards work. With technological progress, the possibilities and demands on standardization are constantly evolving – from improved access to information to machine-interpretable content. Standards and services are thus an essential part of the digital value-added chain.

The development and establishment of such "digital standards" is the overriding goal of current national and international efforts to digitally transform standardization. Due to the complexity of the topic, there are numerous projects with different focuses or approaches. For example, two strategic international groups at ISO and IEC (see Chapter B.3) are concerned with the general feasibility of the digital transformation of standardization. The European CEN-CENELEC Task Force "Digital Content" is gathering practical experience with digital standards in pilot projects. At national level there are pilot projects, workshops, funding projects and tool developments by DIN and DKE, approaching the topic from different directions and with different partners.

The Initiative Digital Standards (IDiS), founded at the beginning of 2020, promotes the digitalization of standardization by bundling IT and transformation topics within the standards organization. In addition to identifying relevant activities, the aim is to support, develop and initiate projects that can contribute to the digitalization of standardization.

The above-mentioned examples show how the Standardization Roadmap is implemented and in which way the SCI 4.0 is fulfilling its role as the key to digital transformation. This Standardization Roadmap will also be regularly updated to reflect new findings, for example as gained in research projects or work within standards bodies, and with the greater involvement of small and medium-sized enterprises. We would therefore like to encourage and motivate you to actively participate in this process.

1.3 Cooperation with the Platform Industrie 4.0

Industrie 4.0 describes a fundamental innovation and transformation process of industrial value creation. Key aspects of this change are new forms of management and work in global, digital ecosystems: Today's rigid and well-defined value-added chains are being replaced by flexible, highly dynamic and globally networked value-added networks with new types of cooperation. Data-driven business models place customer benefits and solution orientation in the foreground and replace product centricity as the predominant paradigm of industrial value creation. Availability, transparency and access to data are central success factors in the networked economy and define competitiveness decisively.

The Platform Industrie 4.0 was founded to drive this transformation and at the same time enable an exchange between all the social actors involved, such as business, politics, trade unions and science.

1.3.1 Designing digital ecosystems – Mission Statement 2030 for Industrie 4.0

As an initiator and moderator of different interests and in its role as an ambassador, the Platform Industrie 4.0 provides an environment for a pre-competitive exchange of information between all relevant actors, business, science, trade unions and associations.

Against this background, the actors of the Platform Industrie 4.0 have decided to formulate a holistic approach to the design of digital ecosystems. The core idea for the design of digital ecosystems is based on three strategic fields of action, which we will classify more precisely below for their importance in the standardization of Industrie 4.0: Autonomy, interoperability and sustainability (see Figure 1) [3].

Although the mission statement focuses primarily on Germany as an industrial and business location, it explicitly emphasizes openness and cooperation with partners in Europe and the world.

By means of a dialogue with all players in industrial society, a framework for action is to be created in order to sustainably shape the digital transformation of Germany's position, building on the globally outstanding starting point of German industry, and to establish Industrie 4.0 economically successfully among German medium-sized businesses.

All three strategic recommendations for action mentioned above are closely linked to the corresponding Industrie 4.0 standardization activities and are interlinked at the appropriate points of the Roadmap.

The strategic areas of action are described briefly below.

Figure 1: Mission statement 2030: Design of digital ecosystems

Autonomy

The guiding principle of sovereignty emphasizes the freedom of all market players (companies, employees, science, individuals) to make self-determined, independent decisions and to act in fair competition with one another – from the definition and design of the individual business model to the purchasing decisions of individuals within the Industrie 4.0 ecosystem. This requires:

→ ***A digital infrastructure:*** This infrastructure must be equally accessible to all participants and available without restrictions.
→ ***Security:*** Data protection, IT and information security represent a firmly established industrial and social value. They are basic requirements for Industrie 4.0 and cooperation within digital ecosystems. In this, industrial security (see **Chapter 3**) is an important quality characteristic.
→ ***Technological development***: Autonomy in Industrie 4.0 requires technologically open research, development and innovation in the core areas of digital industrial value creation. In addition to the technological leadership role of the developments, data protection and security "by design" are particularly important, as are sustainability and interoperability.

Interoperability

The flexible networking of different actors to form agile value-added networks is one of the central core components. A high degree of interoperability, to which all partners in an ecosystem are committed and contribute equally, is a prerequisite for direct operative and process-related networking across company and industry boundaries. Conversely, interoperable structures and interfaces enable both manufacturers and customers to participate unrestrictedly in digital value creation networks and thus ultimately to design new business models.

→ ***Standards and integration***: The integration of individual solutions to system solutions in Industrie 4.0 is based to a large extent on intensive and long-term efforts in the development of standards. This makes integration much easier and therefore provides a basis for interoperability. Not least due to cross-industry reference architectures and the establishment of an administration shell as a digital image of the real world in the digital realm are new approaches available. The further elaboration is now which is now being consistently advanced in the direction of an "USB Standard for Industrie 4.0". (see **Chapter 2.3**)

- → ***Connectivity***: Assets use common communication protocols and the same "connector" between the analogue and virtual worlds.
- → ***Unambiguous semantics:*** Assets understand the meaning and content of information in a uniform manner. They use the same vocabulary, clearly understand the messages they exchange digitally and can communicate in such a way that they interact autonomously and complete the tasks to be performed. (see **Chapter 2.4**)
- → ***Incorporation of AI approaches***: All actors can use and link machine and user data cooperatively. They can also use artificial intelligence to pave the way for new solutions and business models. These include, above all, decentralized systems and artificial intelligence. (see **Chapter 4**)

Sustainability

Economic, ecological and social sustainability are fundamental cornerstones of social value orientation. On the one hand, these aspects are incorporated in Industrie 4.0, while on the other, Industrie 4.0 enables significant progress in sustainability efforts. The ecosystem of innovation and implementation of Industrie 4.0 thus provides the breeding ground for sustainability through Industrie 4.0, as well as for a sustainable Industrie 4.0 itself.

- → ***Good work and education:*** With human beings at the centre, Industrie 4.0 makes significant contributions to the further improvement of working conditions in a dialogue based on social partnership (see **Chapter 2.7**).
- → ***Social participation in Industrie 4.0*** represents a transformative process for society as a whole. This is accompanied by far-reaching changes for participants. The overriding goal is that Industrie 4.0, in terms of industrial and social innovation, not only poses challenges to these participants, but above all opens up new opportunities.
- → ***Climate protection:*** Industrie 4.0 makes it possible to tap additional potentials for resource efficiency. In combination with constructive and process-related approaches, material cycles can be closed over the entire product life cycle. Industrie 4.0 is thus a significant enabler for the circular economy and environmental and climate protection in general. (see **Chapter 2.3.1**)

In linking the fields of sovereignty and interoperability, the Platform Industrie 4.0 has created an important foundation in an international network: Project GAIA-X [4], a distributed, open data infrastructure for Europe. We will refer to the GAIA-X project later in **Chapter 4** on artificial intelligence in industrial applications.

1.3.2 Implementation of the digital ecosystem: Networking central actors

In Germany, in a globally unique approach to date, there is a fast-reacting structure consisting of strategy development and conception, as well as implementation through testing and standardization.

The Platform Industrie 4.0 develops basic concepts in Industrie 4.0-specific working groups on how challenges on the way to Industrie 4.0 can be overcome and provides concrete recommendations for science, business and politics.

The SCI 4.0 takes on the strategic recommendations for action and coordinates their implementation in standards and specifications. The SCI 4.0 thus mediates between the members of the Platform Industrie 4.0 and the various standards organizations. In cooperation with the Platform Industrie 4.0, the SCI 4.0 bundles the stakeholders in Germany and represents their interests in international committees and consortia.

The Labs Network Industrie 4.0 (LNI 4.0) enables small and medium-sized enterprises (SMEs) to implement the strategic recommendations for action, and test new technologies and use cases in pilot projects. LNI 4.0 thus enables the testing and technical and economic feasibility of Industrie 4.0-concepts before market launch. The collaboration between the partners in various test centres makes it possible to generate market-relevant requirements. Validated outcomes are transferred to SCI 4.0 so they can be incorporated directly into the standardization process.

Figure 2 shows how this collaboration works.

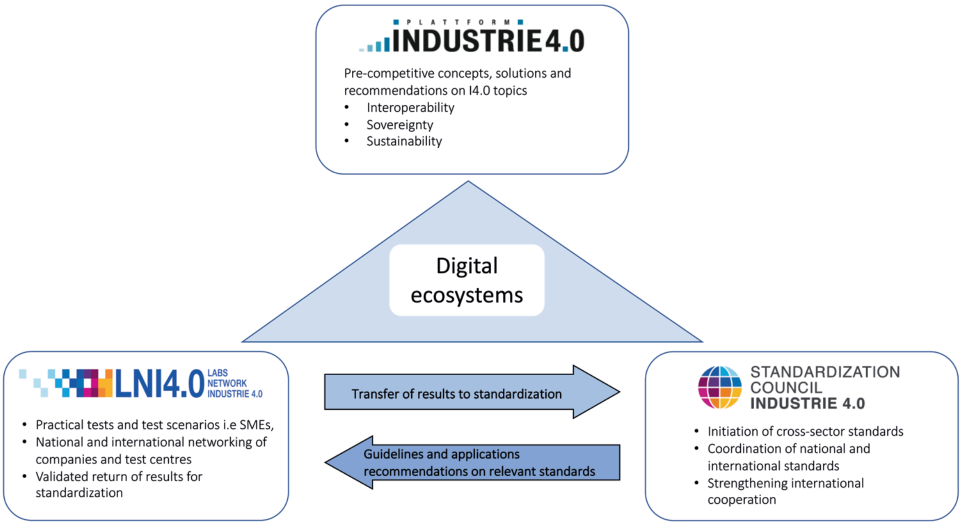


Figure 2: Networking central actors

In the area of internationalization, the Platform Industrie 4.0 and its partners, the Standardization Council Industrie 4.0 (SCI 4.0) and Labs Network Industrie 4.0 (LNI 4.0), promote national and international exchange through numerous bilateral and multi-lateral cooperations.

Through the practical testing of standardization projects in pilot projects, new Industrie 4.0-solutions, and the standards and specifications used in them, can be tested at an early stage. The results are in turn directly incorporated into the further development of these standards and specifications. This approach to agile standardization processes is examined in more detail in **Chapter 3.1.1** under the aspect of open source.

1.4 Significance of application scenarios

Application scenarios are described to illustrate the above-mentioned paths. They show the innovations in technology, work organization, law and society with which German industry wants to enter this digital future. However, the application scenarios also show where the central challenges and questions lie, for example in the areas of standards, research, security, the legal framework and labour, thus providing a common framework.

The result is a systematic picture of the design of Industrie 4.0 and an overview showing where and which developments contribute to the implementation of the strategic goals of Vision 2030 in the form of examples, thus illustrating the first steps towards implementation in the industrial companies towards the realization of the developed vision. Comprehensive collections of Industrie 4.0-specific use cases can be found at Labs Network Industrie 4.0 and Working Group 2 of the Platform Industrie 4.0.

The present Standardization Roadmap Industrie 4.0 takes up the appliation scenarios developed to date and classifies them into an overall technological picture (see **Chapter 1.5**).

From the point of view of standardization, therefore, an ecosystem is considered that consists of a value-added network of companies that offer value propositions to one another and receive a service in return, such as money. In the context of Industrie 4.0 these are:

- Manufacturing companies that offer physical products to consumers or other companies.
- Companies that offer software and services and thus contribute to supporting value-added processes (e.g. providers of logistics services, software applications, engineering or maintenance services) or perform technical integration tasks (such as system integrators).

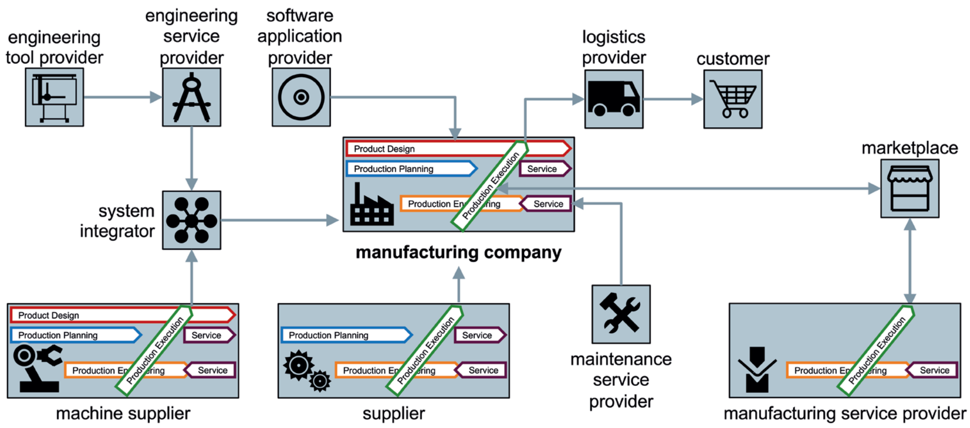


Figure 3: Illustration of a cross-company value-added network

Figure 3 illustrates this value-added network without claiming to be complete. The value-added relationships between the individual companies are indicated by the grey arrows. There is a general conviction in science and business practice that Industrie 4.0 value-added networks and their subsystems will continue to be operated and developed in the long term by humans in a wide variety of functions and roles, i.e. that human activities are and will be an integral part of the Industrie 4.0 value-added process. This significance of human activities and, in particular, the function of humans as idea and impulse generators, enablers, developers, decision-makers and supervisors in Industrie 4.0 value creation systems, must be even better reflected in modelling: in reference architecture models (see **Chapter 2.4**), interoperability (see **Chapter 2.4**), as well as in the areas of work system design, work design and ergonomics (see **Chapter 2.7**).

1.4.1 Examples of use cases

In the following, this value-added network will be explained in more detail using three exemplary use cases. Individual use cases are taken up again in different contexts and discussed in more detail.

Use case 1: "Production marketplace"

In the first example, it is postulated that a new business player will establish itself in the market in the future, for example a marketplace operator who will mediate a supplier of 3D printing on request. The main value-added relationships between the participating companies are shown in **Figure 4**.

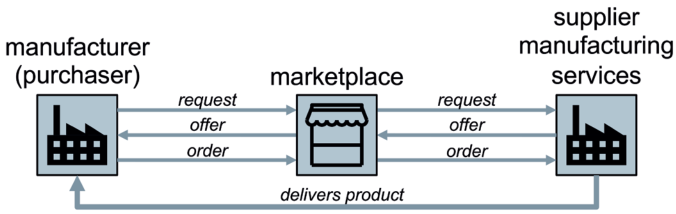


Figure 4: Establishment of a marketplace operator

The benefit for 3D printing buyers is that they can purchase this expertise on the market-place without having to invest in machinery and know-how development. The benefit for the 3D printing provider is that it is granted greater market access via the marketplace.

This example is relevant to this Standardization Roadmap in so far as, depending on the degree of standardization of the requests, the negotiations between the business partners can be automated. Thus, there is the potential to decouple value-added processes that are currently highly intertwined, such as product development and plant engineering, which today are often closely interlinked via "design for manufacturing".

Use case 2: "Integration of a machine tool at the user's site using a standardized description of the manufacturing characteristics"

The second use case illustrates how standardization of manufacturing machines characteristics can simplify te integration of these machines for a user. The main value-added relationships between the participating companies are shown in **Figure 5**.

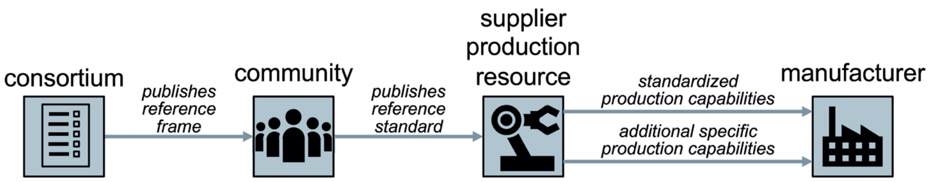


Figure 5: Integration of a machine tool at the user's site using a standardized description of the manufacturing characteristics

A consortium, such as the OPC-Foundation [6] develops a specification. A sector, such as machine tool manufacturers, agrees to develop the OPC UA standard, which is also available as the IEC 62541 series of standards, by developing an OPC UA Companion Specification for their sector. The individual machine tool manufacturers support this and then offer machine tools on the market that have implemented this OPC UA Companion Specification, but that also have unique selling points. The users of machine tools then have the benefit of simplified integration of machine tools in their plant, but also the benefit of cross-manufacturer condition monitoring and predictive maintenance, technology-open production optimization or simplified retrofitting of existing machines.

This use case is relevant to the Standardization Roadmap inasmuch as it can show possibilities of how mechanisms already established on the market should be further developed in order to create added value.

Use case 3: "Assistance system"

Digitalization offers comprehensive technical possibilities to use assistance systems to support types of work involving energy or information: On the one hand, assistance systems, such as exoskeletons or human-robot interaction, are available when performing subtasks that require energy to be exerted, whilst on the other hand, informational assistance systems, such as those used in order to prepare and depict empirically based task descriptions are also available. An exemplary technology for this is data glasses. The means of supporting a specific working activity can be established on the basis of need, and are selected from the facilities to provide support to the two basic types of work. The main value-added relationships between the participating companies are shown in **Figure 6**.

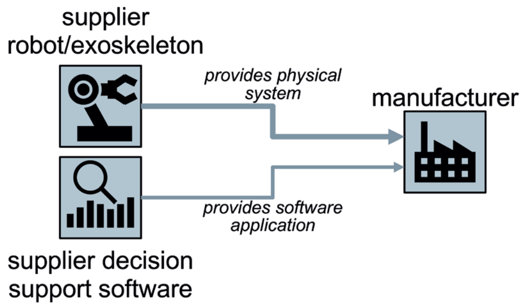


Figure 6: Assistance system

In **Chapter 2.7** this is explained in detail by the example of the final assembly of the interior during automobile production by an assembly employee. This use case refers to the fact that human work continues to play a key role in value-added networks, and that socio-technical aspects therefore play a decisive role in system design and system operation.

This use case shows a concrete need for standardization from an occupational science and systems ergonomics perspective, for example in the areas of data glasses and exoskeletons, human-robot collaboration and assistance systems based on artificial intelligence.

1.5 Technical background – Structure of Chapters 2 and 3

To generate their value proposition, the participating companies use technical systems. But the products supplied by the participating companies are – apart from the services – also technical systems.

Some examples include
- **(mechatronic) systems**, such as a factory or plant, a machine, consumer goods such as cars, or food, or components such as drives, as well as screws and washers
- **hardware and software systems**, such as plant control systems, engineering tools for product and plant design, information platforms for the systematic collection of data, including software tools for data analysis to gain new insights

These technical systems are usually made up of other technical systems and interact with each other in many ways. Many of these technical systems are carriers of different types of information and via technologies such as communication technologies or cloud platforms, and possibilities are created to transfer such information between the technical systems along corresponding interrelationships. This is illustrated in **Figure 7** on the one hand schematically and generally without claiming to be complete, and on the other hand, possible interpretations of these technical systems and their interrelationships are shown in blue font as examples:

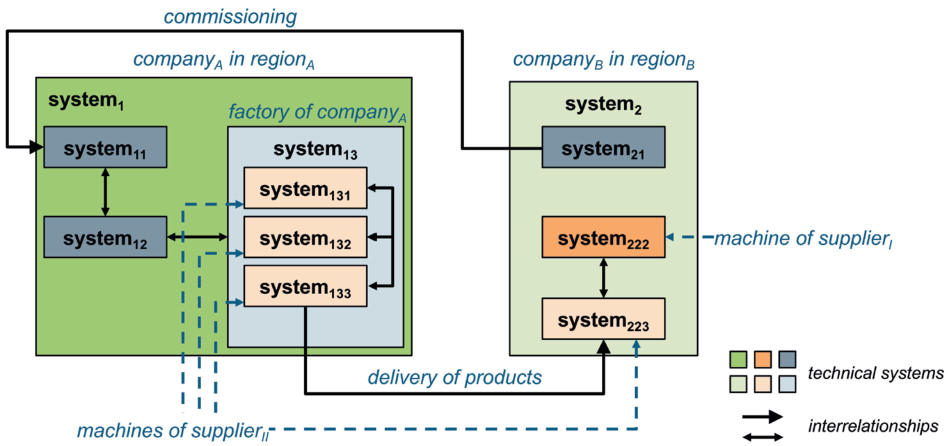


Figure 7: Technical systems and their interrelationships

In summary, it is therefore necessary to develop standards that allow different systems to be developed independently of each other while still ensuring interoperability between them (see **Chapter 2.4**). In addition, standards make it possible to replace individual components of a complete system with little effort and thus migrate in steps from an installed basis to a target landscape. At the same time, standards must ensure that sovereignty over their own systems is maintained so that the basis for sustainability is created overall.

From the design principles of the digital ecosystem and from the perspective of national standardization, based on the structure of the the Reference Architecture Model Industrie 4.0 (RAMI 4.0) [7], the individual aspects of the Standardization Roadmap in **Chapter 3** are derived from the following considerations. The considered value-added network is complex and it is necessary to have an understanding of the characteristic and representative features of this value-added network. It has proven to be useful to describe this by means of use cases. Since these use cases are developed independently by different interest groups, it is purposeful to create a general framework for the description of use cases, which is described in **Chapter 2.1**.

The technical systems used and considered according to **Figure 7** are diverse and partly also very complex. Since these systems are developed independently of each other, it makes sense to agree on general models according to which such systems are constructed in the sense of a reference architecture**.** In addition to the system view, the architectures also deal with embedding in their context and consider not only the associated processes, but also the actors involved in these processes. This is described in **Chapter 2.2**.

For the various systems used as shown in **Figure 7**, it is expedient to classify them according to general principles and to standardize the characteristic properties of these different systems across the board, which is described in **Chapter 2.3**.

For systems to be able to interact at all, the individual systems must be designed to be interoperable. The data and information exchanged between the systems are on the one hand diverse, and on the other hand sometimes very complex, such as product descriptions. It is therefore expedient to agree on principles on the basis of which the structure and meaning of this information are formalized. Although the interactions require communication systems, they should be independent of the technological implementation of the communication. This is discussed in detail in **Chapter 2.4**.

As illustrated in **Figure 7**, technical systems are composed of other technical systems that are usually provided by other companies. It is therefore expedient to agree on interfaces according to which such integration takes place. This applies in particular to integration from the IT perspective, which is described in **Chapter 2.5**, and specifically for industrial safety, which is described in **Chapter 3.**

The systems shown in **Figure 7** must interact with each other. A necessary prerequisite is that they transport data and information between the systems. This includes the aspect of networks and includes industrial communication systems (e.g. fieldbuses like PROFIBUS and Industrial Ethernet like PROFINET) as well as middleware technologies (e.g. OPC-UA), see **Chapter 2.5**). The standardization of communication systems is already very advanced and is therefore not considered further in this Standardization Roadmap. There are a number of middleware concepts and solutions. It can be assumed that the market will lead to a consolidation here.

In the various value-added processes shown in **Figure 2**, humans are involved in the planning and execution, whether as engineers or workers. The definition and development of recommendations and standards for human-friendly work, process and product design in Industrie 4.0 is described in **Chapter 2.7**. Existing standards are to be identified, reviewed and, if necessary, updated, and new fields of work are to be identified. This includes, in particular, topics such as new forms of work organization, adaptive design of work systems in Industrie 4.0 and software usability.

Figure 8 illustrates the relationship between interoperability (see **Chapter 2.4**), integration (see **Chapter 2.5**) and communication (see **Chapter 2.6**).

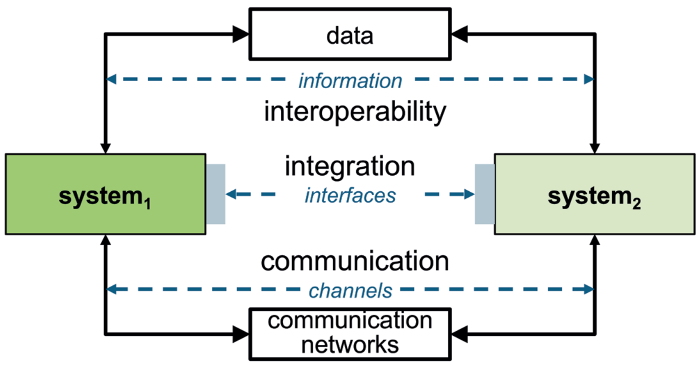


Figure 8: Relationship between integration, communication and interoperability

Within the framework of accompanying standardization activities and research projects, cross-cutting issues of importance to Industrie 4.0 (**Chapter 3**), including the standardization needs in the core topics integration, communication and interoperability, will be linked together.

As in the previous edition of the Roadmap, cross-sectional topics are described in more detail, which cover all layers of the reference architecture model RAMI 4.0 (see **Figure 9**):

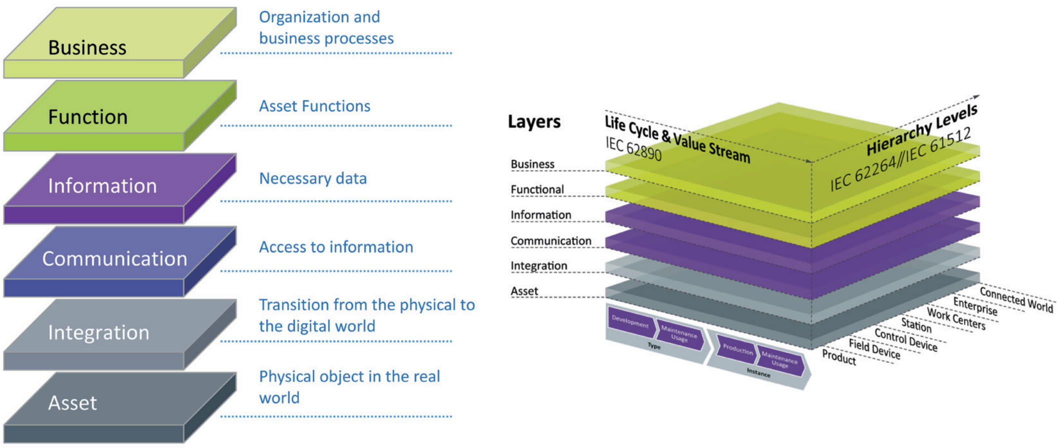


Figure 9: Layers of the RAMI 4.0 model

- When implementing software applications, companies increasingly rely on **open source** software. This is the best way to save costs, drive innovation, accelerate knowledge transfer and improve interoperability. In addition to independence from individual software providers, timely updates and the ability to customize the software play an important role. For this reason, **Chapter 3.1** discusses current open source projects in more detail.
- The protection of information security is indispensable for the reliable functioning of an industrial facility. Attacks on control devices or the data to be processed can lead to considerable damage to people and the environment, paralyze infrastructures or damage the know-how base of a company. In the context of Industrie 4.0, the increasing interaction between the companies involved significantly increases the need for protection. **Chapter 3.2** is devoted to the resulting additional recommendations for action on **industrial security.**
- In the industrial context, **privacy** has so far been mainly considered as employee data protection, because systems record employee activities. Industrie 4.0 expands the field of application of privacy, because business-to-consumer value-added processes are linked with manufacturing systems, for example in the production of individualized products. Standards must therefore be compatible with regulatory provisions so that privacy functions can be integrated into processes from the outset. **Chapter 3.3** recommends corresponding actions.
- The **trustworthiness** of all business partners and their contributions along the entire value-added chain ultimately determines the quality and reliability of the final result. Trustworthiness particularly affects characteristics such as reliability, security, functional safety and privacy. Each participant is dependent on the trustworthiness of their supplied components and can make a value promise about their own value contribution. Trustworthiness can be measured and verified within certain limits by means of standards and certification processes. Current developments and recommendations for action are presented in **Chapter 3.4**.

→ In **Chapter 4.1**, we discuss the use of AI in industrial applications for the first time. Depending on the application and function of the AI, this can influence the compliance with requirements described in standards. For example, if AI technology is used to adapt the behaviour of automated functions, the influence of the AI's actions on the automated system must be taken into account in the conformity assessment. This applies in particular to industrial applications with functional safety requirements. Consequently, it is necessary to always check and ensure the fulfilment of normative framework conditions, especially considering the function and influence of AI. An objective assessment of the AI's sphere of influence is particularly necessary in this context.

2 Need for standardization on core topics

2.1 Use cases

2.1.1 Status and progress since Version 3

There is now a growing international consensus that new standardization activities are particularly useful if the underlying driving use cases are formulated and clearly understood. In this respect, an internationally uniform understanding of use cases in the context of Industrie 4.0 is a central starting point in standardization work. Use cases are an instrument here to build a bridge from the driving challenges facing the manufacturing industry to the corresponding possible technical solutions. Use cases then also offer the possibility of deriving new requirements for standardization.

The "modern" understanding of the term "use case" derives from the document "Concept Use Case 2.0" [5] published in 2011. It describes a scalable, agile technique for developing requirements with which incremental system development can be controlled.

For many companies they are the tool of choice for stakeholder communication. They help to understand how a system contributes to the achievement of the user's goals and produces the desired results. The added value of use cases lies in the integration of established requirements engineering techniques into an agile approach. Use cases thus offer many advantages even in agile projects.

The importance of use cases was also recognized and evaluated very early on by the Platform Industrie 4.0. In Germany, for example, use cases were collected in the form of implementation examples, prepared and presented on an online map [6]. This approach was then taken up and implemented by other countries.

Furthermore, a conceptual separation of problem descriptions and solution approaches was recognized early on, and this was taken into account in the formulation of "application scenarios". It was also stressed that due to the diversity of the manufacturing industry not every use case has the same relevance for every user, and that a problem description can be implemented in different ways.

On the other hand, it became increasingly clear that the term "use case" was understood and used in very different ways. Among other things, this has led to Version 3 of the Standardization Roadmap Industrie 4.0 containing a separate chapter on "Use Cases" for the first time. The core of this recommendation is a proposal to basically distinguish between three different categories of use cases:

- → **Business scenarios**, where value-added relationships between companies and their business models are described from a business perspective.
- → **Use cases,** where a technical system is described in its application context, namely how actors outside the technical system interact with it and with each other.
- → **Practical examples**, where a concrete solution is described.

This suggestion has been actively taken up and implemented both nationally, for example in selected use cases of Labs Network Industrie 4.0, and internationally, particularly in the context of cooperations with the USA, China and Japan.

2.1.2 Current developments

The use of the instrument of use cases has recently gained additional momentum and is being discussed more widely than two years ago in connection with the preparation of Version 3 of the Standardization Roadmap. This has naturally led to the fact that the understanding of what is meant by a use case in detail has by no means been consolidated, but rather, this subject matter has become even more complex.

When describing use cases, the discussion about the template used often has a high priority, but once a template has been agreed upon, it is sometimes not filled out very "conscientiously". In general, the formulation of concrete high-quality use cases is complicated. One should always be aware of this necessary complexity in advance.

In general – due to the resources available – the focus seems to be on the formulation of use cases which should be formulated in a rather "simple" or "lightweight" manner. This may be the reason why the "application scenarios" of the Platform Industrie 4.0 have not developed significantly, because on the one hand the representation of the existing application scenarios is already quite good – and thus there is no acute need for action – and on the other hand the development of a high-quality application scenario is very costly. Even the template according to IEC 62559-2 is currently not widely accepted in Industrie 4.0, as it requires a great deal of effort to fill out a use case in this level of detail and, to make matters worse, due to the breadth of the topic Industrie 4.0, many such different use case descriptions would be necessary to obtain a representative collection of use cases.

In particular, activities in which business scenarios are described have recently increased. Fortunately, business scenarios are a tool to enter into discussions about Industrie 4.0, especially with management, so that additional momentum can be expected from this direction.

In this environment, it is now the task of standardization to find a goal-oriented path for itself [see RE 2.1-A1]. It is therefore imperative to agree on why use cases should be compiled and consolidated in the context of standardization:

In the past, standardization activities were often only initiated when solutions had proven themselves in practical use. In contrast, especially in the IT standardization environment, solutions are often initiated at a time when they have yet to be launched on the market. It is therefore important to get a clear picture of future applications from a standardization perspective. In order to create standards under the premise of both market relevance and binding status, such use cases must be sufficiently precise and representative

Standardization can of course take up impulses from activities in which use cases are collected and described under various objectives. However, it is the original task of standardization to consolidate this input with regard to the necessary precision. This is an absolute necessity from the perspective of standardization.

The value of a consolidated set of use cases for standardization is as follows:

→ *Consolidation of the Industrie 4.0 vision:* the use cases describe the basic principles of traditional and future value creation processes in the manufacturing industry, and systematically postulate additional possibilities made possible by digitalization. Consolidation of terms and concepts: By means of the use cases one can agree on basic terms and concepts and explain them in an application context in their interrelationships.

- → *Justification of a general need for standardization:* through the use cases, fundamental gaps in standardization which are to be closed can be identified. However, certain potentials can already be exploited through the consistent application of existing standards and specifications.
- → *Formulation of requirements for standardization*: requirements – and not solutions – are identified via the use cases. Measures initiated thereupon for the further development or new development of standards and specifications can then be consistently linked to the corresponding requirements.

Consequently, use cases are a central element in the design of future standardization. In view of the original objectives of standardization, it is therefore recommended that the concept of a common understanding of use cases be continued as shown in **Figure 10**.

Use cases are also a central element with regard to methodical system development in the context of Industrie 4.0 using system architectures. Here, however, it can be observed that other domains, such as the Smart Grid, are using this methodology more systematically and comprehensively. This may be due to the fact that the manufacturing industry is more complex than the Smart Grid, but this is also an indication that, in the future, the use cases arising in the environment of the manufacturing industry should be further detailed.

For a better understanding and classification in this context, a brief look will be taken at the relevant work. As early as 2016, the Platform Industrie 4.0 and the Industrial Internet Consortium (IIC) had produced a white paper [7] that focused on the complementarity of the two reference architectures. The concept of the Industrial Internet Reference Architecture (IIRA) [8], emphasizes cross-industry similarities and interoperability across industries, while RAMI 4.0 focuses on the value chains in the manufacturing industry – and thus one industry (see **Figure 10**).

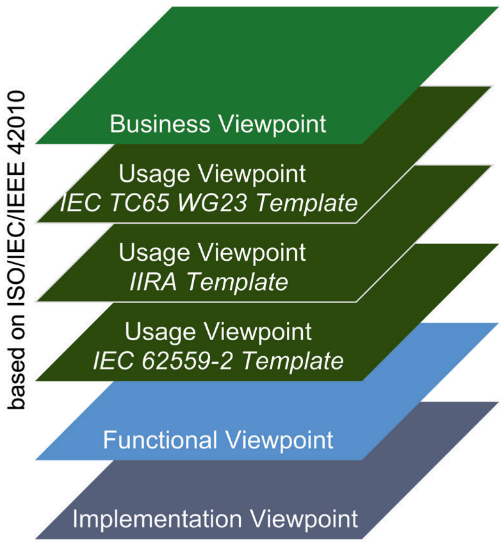


Figure 10: Description of use cases from various perspectives

RAMI 4.0 essentially focuses on the functional viewpoint according to IIRA, so that the business and usage viewpoints according to IIRA are additional perspectives that can and should be taken and described for an IIoT system in the manufacturing industry.

Furthermore, one of the central recommendations is to distinguish between business scenarios, use cases and practical examples. A comprehensive understanding of the business-driving, business-oriented applications for I 4.0 is necessary, especially with regard to standardization. However, due to the complexity of value-added processes in the manufacturing industry, the previously recommended templates according to IIRA and IEC 62559-2 are too powerful, so that the use of the IEC TC65 WG23 template is proposed as a systematic top-down approach [see **RE 2.1-1**].

In this context, the two use cases 1 "Production marketplace" and 2 "Standardization of the production properties of machines" are described in detail in **Chapter 2.2**.

Note that there are well-defined relationships between the different templates for the usage viewpoint, as shown in **Figure 11**. The IIRA template is a refinement of the IEC TC65 WG23 template and the IEC 62559-2 template is a refinement of the IIRA template.

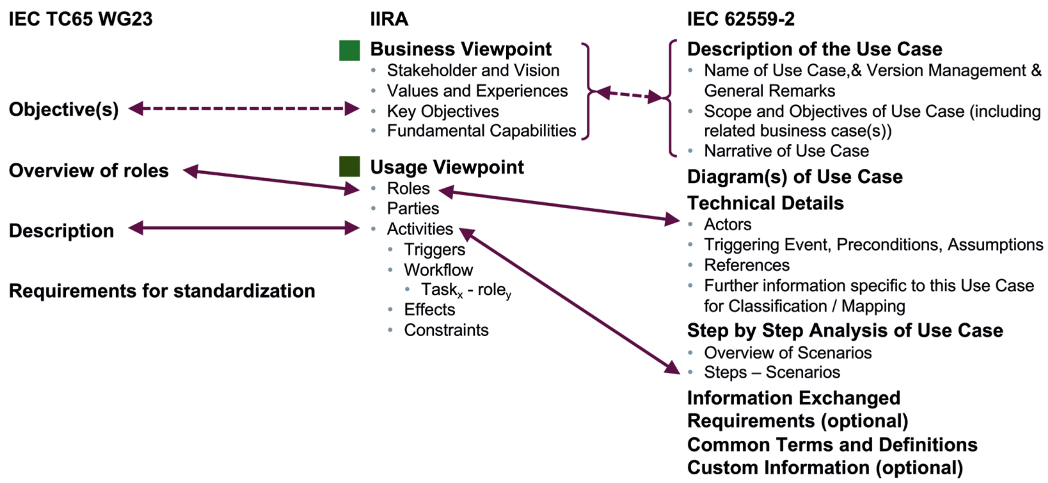


Figure 11: Refinement relationships between the different templates

Selected reference examples of business scenarios and use cases based on this overall understanding are listed below:

→ **Business Viewpoint**: the application scenarios of the Plattform Industrie 4.0 [9] and the detailed descriptions of the application scenarios "Value-based Service" [10] and "Seamless dynamic plant engineering" [11] are worth mentioning here. In addition, we would like to point out the business scenarios which are based on the methodology of the working group "Digital Business Models" of the Platform Industrie 4.0 [12] which is used in several working groups, especially in cooperation with China [see **RE 2.1-A2**].

→ **Usage Viewpoint according to the IIRA Template**: as mentioned at the beginning, the usage view is not only considered in exchange with the IIC. The design of the usage view is currently being deepened and refined in bilateral national cooperations. For example, joint descriptions of "Usage view mass customization" und "Usage view equipment lifecycle management" [13] were refined and evaluated in the German-Chinese subworking group Industrie 4.0/Intelligent Manufacturing [14]. As part of the Japanese-German cooperation between the SCI 4.0 and the Japanese Robot Revolution & Industrial IoT Initiative, descriptions such as "Usage view value-based service" [15] and "Usage view asset administration shell" [16], were developed. This work is complemented by the description currently being developed by Labs Network Industrie 4.0 "Usage view edge configuration" [see **RE 2.1-2**].

→ **Usage Viewpoint according to the** IEC 62559-2 **template**: the descriptions "Plug-and-produce for adaptable factories" by the Platform Industrie 4.0 [17] and "Functional View Value-based Service" of the Robot Revolution & Industrial IoT Initiative and the Platform Industrie 4.0 [18] are mentioned here.
Finally, it should be emphasized that the systematic consideration of socio-technical aspects in the formulation of use cases, for example a refinement of use case 3 "Assistance system" in **Chapter 2.2**, is a purposeful approach to arrive at a joint discussion on additional forms of Industrie 4.0 [see **RE 2.1-2, RE 2.1-A3**].

2.1.3 Recommendations for action and application

2.1-1 The Task Force "Smart Manufacturing Use Cases" of IEC TC65 WG23 should be actively supported by Germany in order to obtain a consistent and representative use case collection for Industrie 4.0. This will help the task force to establish itself as the central hub for a systematic consolidation of the many different use cases in the Industrie 4.0-environment.

2.1-2 The various activities that formulate use cases based on more detailed descriptions such as the IIRA template should be continued. Examples are the joint activities with China and Japan, selected activities of Labs Network Industrie 4.0, but also activities at European Union level, such as those planned in particular in the context of artificial intelligence within the AI-PPP.

2.1-A1 Efforts should continue to be made to avoid overloading the term "use case" unnecessarily. It is not the aim to prescribe a uniform understanding, but it is recommended that activities position themselves in relation to the understanding formulated in this standardization roadmap so that this can be further enhanced.

2.1-A2 It is recommended to further promote the formulation of business scenarios, as is especially promoted in cooperations with China, since business scenarios are not – at least at the moment – within the scope of WG23 of IEC TC65.

2.1-A3 The discourse on the importance of socio-technical aspects in industrial applications is becoming increasingly important. Against this background, it is important to further intensify a discussion on Industrie 4.0 with regard to use cases and business scenarios.

2.2 Reference architecture models

2.2.1 Status and progress since Version 3

The modelling of reference architectures is an effective approach to systematize and simplify the reproduction of essential and often complex structures and functions. The aim of standardization in this subject area is to create a standardized framework to which technical components from different manufacturers conform. This will not only enable efficient data exchange in industrial environments, but also an uncomplicated use of data across different infrastructures.

Reference architecture models provide a logical framework and the necessary mechanisms and tools to support the development of a new technical system or the modification of an existing system throughout its life cycle.

The framework should essentially contribute to smooth cooperation between the various stakeholders in digital ecosystems. As applied to use case 1: "Production marketplace", a reference architecture model should consider all players and their interrelationships, including hardware and software components, user and supplier industries, and product design through to product recycling of a 3D product.

In computer science, a reference architecture acts as a reference model for a class of architectures. An architecture (e.g. enterprise IT architecture, cloud architecture, IoT architecture etc.) determines the structure of a system on two levels: 1) The object level, including the structuring of the system into specific subsystems, and (2) the rule level to be observed in the development of the system. It thus defines the meta-level of development, e.g. through patterns. This means that a reference architecture is regarded as a specific model pattern, i.e. an ideal-typical model for a certain class (e.g. "IoT", "Cloud", "IT") of the architectures to be modelled. It covers both operational and functional aspects of that particular class. For this reason, a reference architecture model does not specify "the" architecture per se, but only the framework with minimum requirements or aspects.

In the following, this chapter deals in more detail with past and current standardization activities and explains the main recommendations for application and action in this area. In recent years, several specifications for reference architecture models for various purposes in the environment of Industrie 4.0 have been presented, including the reference architecture model Industrie 4.0 (RAMI 4.0) (see Figure 12).

In the meantime RAMI 4.0 has been successfully introduced as international specification IEC PAS 63088 in national and international standardization committees and cooperations. Thus, a first premise to develop a model that allows the representation of an object of the physical world in the information world in order to be able to manage it in this world was fulfilled. On this basis, it was possible to position IEC PAS 63088 with RAMI 4.0 and the administration shell among the internationally adequately developed reference architecture models of other countries. Subsequently, the ISO/IEC Joint Working Group 21 (ISO/IEC JWG 21) was constituted in order to consistently design and combine into reference architecture models the numerous national standardization activities (France, China, Japan, USA, South Korea, Sweden) within ISO and IEC.

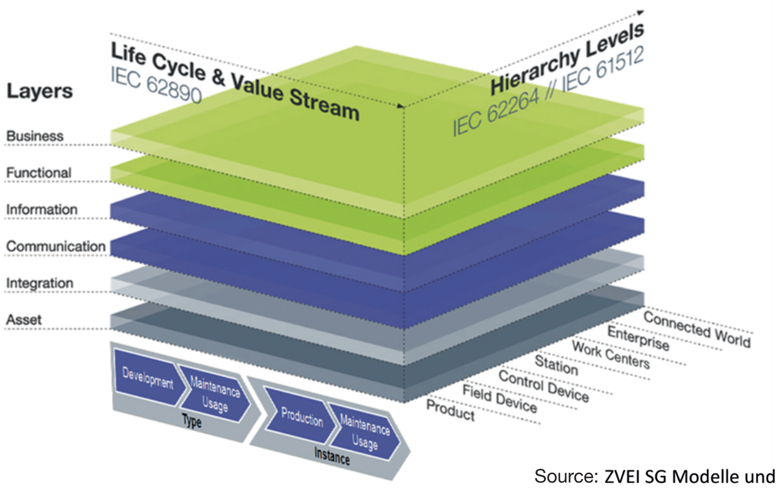


Figure 12: RAMI 4.0

Reminder: RAMI 4.0 (IEC PAS 63088)
RAMI 4.0 serves as an orientation framework for the stakeholders and classification of applications in the industrial sector. RAMI 4.0 introduces all elements and IT components in a layer and life cycle model and divides complex processes into manageable packages – including data protection and IT security. The reference architecture can be regarded as a model pattern, i.e. an ideal-typical model for the class of architectures to be mod-elled. Industrie 4.0 does not specify "the" architecture per se with RAMI 4.0, but only the framework with minimum requirements. This includes the definition of terms and a methodology with rules for describing the physical world for the purpose of mirroring (reflection) into the information world.
[see The Reference Architecture Model RAMI 4.0 and the Industrie 4.0-component] [19]

2.2.2 Current developments

With the current development of the Technical Report (TR) Smart Manufacturing Meta-Model "A Meta-modelling analysis approach to Smart Manufacturing Reference Models (SMRM)", the recommendations for action formulated in Version 3 of this Roadmap in 2018 have already been implemented by IEC/TC 65/JWG 21. The additional ongoing standardization developments of further reference architecture models are now focusing their activities on networking with those of the IoT world. Some of these activities are shown in the overview below and again illustrate the degree of networking and thus the degree of increasing complexity (see Annex A)

The main objective of these activities is to develop a strategy to harmonize current standards for reference architectures in order to achieve a common understanding of the characteristics of reference architecture models and related standards.

These activities cover such important topics as big data, federal cloud computing, secure data exchange, system architectures and others. As a result, new reference architectures are constantly circulating, which could possibly be assigned to an already existing reference architecture model. Similarly, new reference architecture models are often not compared or aligned with the existing ones [see RE 2.2-1, RE 2.2-2].

As a result – because there is still no broader and deeper understanding of the essential differences between terms such as "reference architecture" and "reference architecture model" – there is currently confusion in the application of these terms and naming of new standards. This area is to be harmonized [see RE 2.2-3].

Harmonization and compatibility of new and existing reference architecture models

From the very beginning, the interweaving of RAMI 4.0 with the IoT world has been at the centre of the considerations of the working groups of the Platform Industry 4.0, which continues to develop new documents on this complex of topics. Here, comprehensive technical principles are described for the realization of Industrie 4.0 value-added networks in which objects of the physical world are described according to RAMI 4.0 for their representation and administration in the information world as I 4.0-components.

The heterogeneity of solutions for reference architecture models was already pointed out in the previous edition of this standardization roadmap. There was and still is a need for harmonization, especially in the Industrie 4.0-environment. At international level this is being dealt with in working groups and committees such as ISO/IEC JTC1/AG8, ISO/IEC JWG 21 and ISO/IEC JTC 1/SC41. The main objective of these activities is to develop a strategy to harmonize current standards for reference architectures in order to achieve a common understanding of the characteristics of reference architecture models and related standards.

Here is an overview of these activities.

→ ISO/IEC JTC1

Meta Reference Architecture and Reference Architecture for System Integration

WG 08 is dealing with harmonization concepts on the meta-level, in particular with the investigation of current procedures for the development of reference architecture and meta-reference architecture in JTC 1-relevant system integration contexts. The WG 08 also focusses on the development of definitions, concepts, processes, models and templates for the meta-reference architecture, as well as on cooperation with relevant standardization organizations, and the development of recommendations for JTC 1 for successful system integration using the developing meta-reference architecture. To avoid duplication of work, these activities should be coordinated with the parallel activities of ISO/IEC JWG 21 (see below) [see RE 2.2-1].

→ ISO/IEC Joint Working Group 21

Smart Manufacturing Meta-Model

"A Meta-modelling analysis approach to Smart Manufacturing Reference Models (SMRM)" presents a metamodeling approach for the analysis and description of smart manufacturing reference models. It refers to the specific area of smart manufacturing in general Industrie 4.0-environments, which results in a clear separation in terms of the industrial IoT. Currently, the report identifies 17 relevant reference architecture models. Based on these analyses, further aspects from the field of "*smart manufacturing*" are identified and transferred to the SMRM. On this basis, the SMRM can be characterized as a "meta-language" of concepts and important relationships, which offers the smart manufacturing user freedom over abstraction. [see RE 2.2-2, RE 2.2-3]

→ ISO/IEC JTC 1 SC41 Industrial Internet of Things IIoT

Reference Architecture for IoT

A central role in the industrial IoT is played by sensors, actuators and technical systems that collect production data and distribute it via the network, where it can be further processed using algorithms at the cloud computing level.

One of the most important IoT standards is ISO/IEC 30141 Reference Architecture for IoT, published by ISO/IEC JTC 1 SC41. The standard provides a standardized IoT reference architecture based on the vocabulary (ISO/IEC 20924) and a generic design using industrial best practice applications. The standard serves as a basis for the development of context-specific IoT architectures, and thus also for industrial sensors, machines, plants and other technical systems. The generic design of the concept can be extended to other industry-specific areas, including specific technological requirements and national applications.

→ ISO/IEC JTC 1 AG 20 Industrial IoT

Standard mapping for reference architecture models

To support harmonization activities at the international level, various activities are currently being carried out in ISO/IEC JTC 1 SC 41 WG 20 Industrial IoT with the aim of standard mapping. Thereby the relevant IoT standards are divided into the corresponding RAMI 4.0-layers and other relevant areas in the context of Industrie 4.0. The mapping is intended to provide an overview of the current standards landscape and uncover possible standardization gaps in the area of industrial IoT. Such an activity requires very good cooperation between numerous bodies and should be supported by other activities, such as industrial practice and research [see RE 2.2-A1].

2.2.3 Recommendations for action and application

2.2-1 Use of RAMI 4.0 in requirements management

It is recommended to investigate and describe the use of RAMI 4.0 in comparison with other common methods for a continuously structured requirements management.

2.2-2 Differentiation and standardization of the terms "reference architecture" and "reference architecture model"

A deeper understanding among SDOs and consortia, as well as corresponding standardization activities (such as inclusion in a glossary), regarding the differentiation of the terms "reference architectures" and "reference architecture models" seems necessary. The generated model patterns of a reference architecture can be differentiated according to the class of the architectures to be modelled. This means that there is an operational and functional differentiation between reference architectures and reference architecture models. A uniform understanding of this must be created in standardization and laid down in standards.

2.2-3 Harmonization and compatibility of new and existing reference architecture models

There is currently a need for harmonization due to the heterogeneous solutions for reference architecture models in the Industrie 4.0-environment. It is recommended that the reference architecture models (both existing and new) are critically reviewed for functional and operational aspects, i.e. whether they are already covered by existing models. However, if the functional and operational aspects do not correspond, no further harmonization activities should be undertaken. The activities of ISO/IEC JTC1 WG08 and ISO/IEC JWG 21 are thus to be coordinated.

2.2-A1 Standardization in Industrie 4.0-relevant research programmes
It is recommended that research projects, both national and international, actively apply the current standards in order to enable faster industrial implementation and to identify possible standardization gaps.

2.3 Systems and their properties

2.3.1 Progress since Version 3 and current developments

The Industrie 4.0-component and the concept of the administration shell

In order to make the information world available, objects are described by means of their properties in such a way that this description can be assigned to the respective object in the information world as a whole and placed in relation to other objects. According to the concept of the digital factory (IEC TS 62832-1), a physical or logical object that has an actual or perceived value for an organization and is therefore managed is called an asset.

The properties of an asset are structured in their "asset administration shell" according to RAMI 4.0 (see **Chapter 2.2**). Assets and their administration shell are uniquely related to each other. Together they build the "Industrie 4.0-component" or "I 4.0-component" for short (see **Figure 13**). The administration shell can be stored in the asset or in a database.

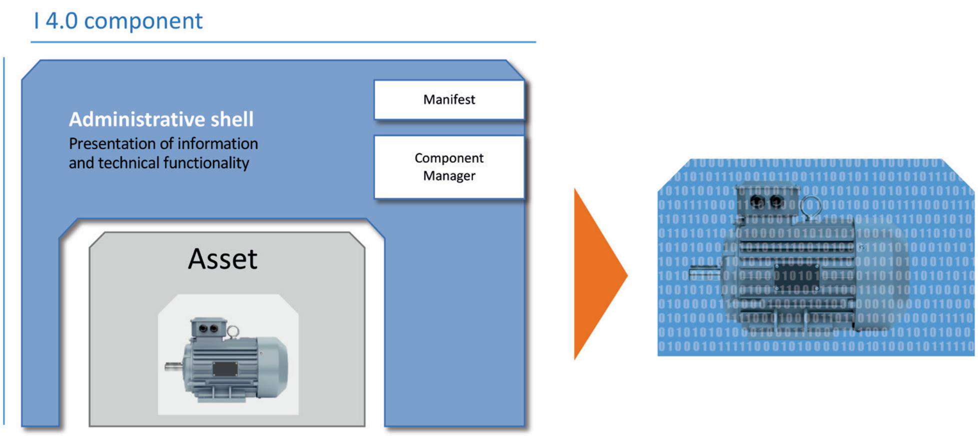


Figure 13: Industrie 4.0-component with asset and administration shell

Assets can be physical objects such as devices, lines, etc., but also intangible things such as software, concepts, patents, ideas, methods, processes. It can be a simple asset (e.g. a pipe), or a modular asset (e.g. machine, plant, factory). For example, the (self-)description of the machine tool from **Use Case 2** in **Chapter 2.1.1** should be reproduced in the administration shell of this machine.

The term "*administration shell*" is based on the idea that the information world encloses the asset (e.g. part of an I 4.0-component) like a shell [4]. (See **Figure 14**).

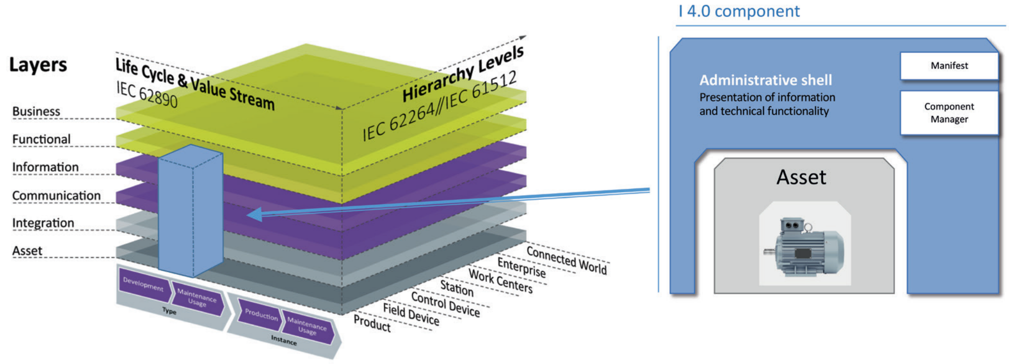


Figure 14: I 4.0-component and its classification across the corresponding RAMI layers

As was shown in the introduction, such an I 4.0-component can represent a machine tool, for example. The information is stored using properties whose semantics are defined so that the system can standardize the relevant information and make it available via the corresponding RAMI 4.0-layers.

The original conceptual structure of the administration shell was presented by the *Working Group Reference Architectures, Standards and Standardization* in cooperation with the ZVEI in the findings paper "Structure of the Administration Shell" [79]. The paper does not contain a final IT specification or implementation requirement and was initially used to clarify what properties, data and functions are typically stored in an administration shell.

The document "Details of the Asset Administration Shell" (Part 1, Version 1.0) [86] describes the preparation and structuring of information in the administration shell. The aim of this document is to specify the structure of the administration shell so that information about assets and I 4.0-components can be exchanged between I 4.0-components in a value network. The document defines the structure, that is, the serialization and exchange format of an administration shell. Part 1 of "VWSiD" with "Details of the AAS" focuses on the exact definition of the data model using a UML diagram, its serialization in XML and JSON, and the definition of a simple and secure transport of administration shells between two technical infrastructures in a container. (See **Figure 15**).

The extended version 2.0 [28] of the first version, published in 2018, describes how companies can prepare and structure information in the administration shell. The updated version informs about a variety of interesting topics like RDF implementation and AML and OPC UA mappings, which were developed together with AutomationML e.V. and the OPC Foundation.

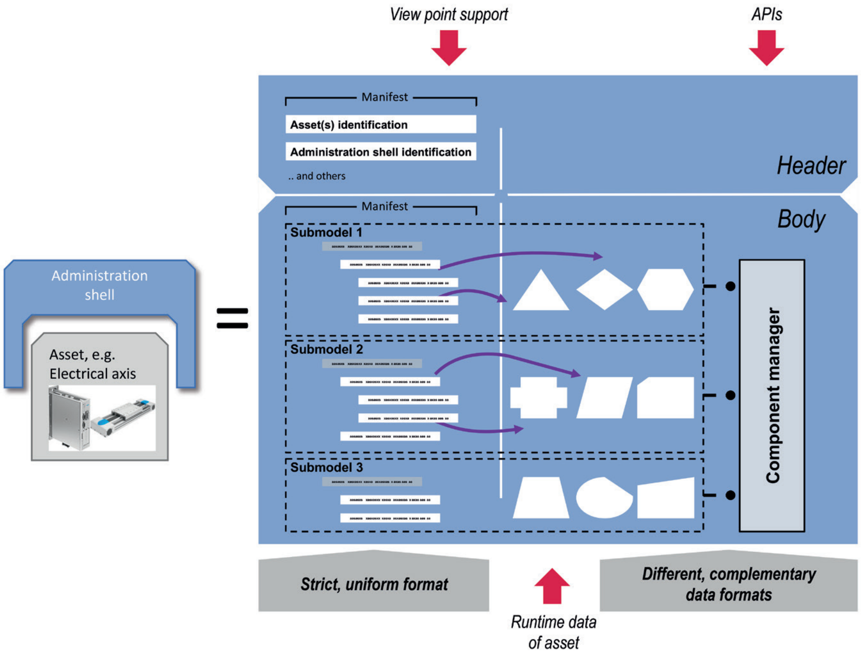


Figure 15: Structure of the administration shell and possible sub-models

The content and essential part of an administration shell are the sub-models. There are different classes of sub-models, which are explained in detail below. Which sub-models an administration shell supports depends largely on the type of asset, the life cycle and the application scenario. Sub-models have a unique assignment to the administration shell, a unique ID and thus also a unique reference to a concrete asset.

Generic requirements for sub-models

Sub-models essentially consist of properties and references to functions, methods, services, documents and other complex content that is not part of the sub-model itself. If possible, sub-models should have a complete view of an aspect of the asset and a certain benefit or serve a scenario. An example of this is energy management, so that all relevant properties can be provided via interfaces in the energy management sub-model.

Besides the contents of the administration shell, the mechanisms for communication and integration play a decisive role. The interoperability of I 4.0-components depends largely on the content of the administration shell. Thus, the main task of the administration shell is to register and make available the data and functions of all relevant assets – including products and entire production systems – in a standardized way throughout their life cycle. At IEC/TC 65 the project IEC 63278-1 ED1 "Asset administration shell for industrial applications – Part 1: Administration shell structure" was started in the newly founded IEC/TC 65/WG 24 to describe these concepts in an international standard. This sets the course for developing the concepts of the administration shell into an international standard or series of standards. The standardization proposal takes up the documents "Trilateral Perspectives: Structure of the Administration Shell" and "Usage view of Asset Administration Shell". The Platform Industrie 4.0 and SCI 4.0 have developed these together with international partners (France, Italy, China and Japan). Further parts of the IEC 63278 series and other standards are required to internationalize the concept of the administration shell. This involves both the description of infrastructure mechanisms, such as the I 4.0-language, as well as the description of sub-models for specific classes of assets [see RE 2.3-8].

Current national and international activities are aimed at further elaborating the administration shell in detail. In the meantime, the Platform I 4.0 working group has published several specifications containing specific aspects and practical assistance.

The publication "Administration Shell in Practice" [29], on the other hand, summarizes the essential aspects of the content of the administration shell and shows how companies can use and manage data in Industrie 4.0 in a standardized way and how they can put this into practice. The central goal is to provide the user with guidance on how to specify sub-models, exemplary submodels and interaction between administration shells.

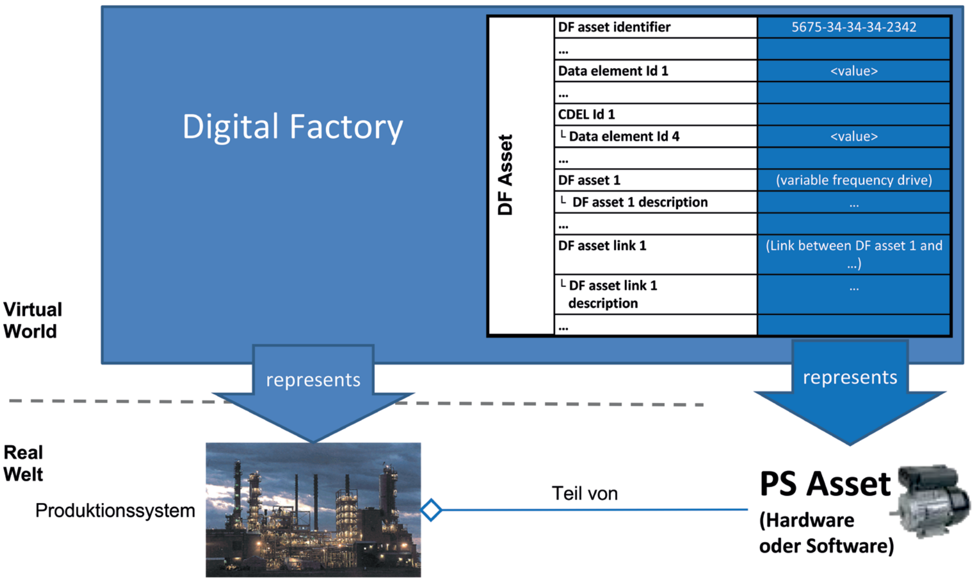
The concept of the administration shell should be consistently used and standardized for smooth data exchange with and between assets [see RE 2.3-1]. In further developments, agent-based systems should also be transferred to Industrie 4.0-components. The individual specifications and descriptions are dealt with in Chapter 2.5.1.

Digital factory

The international standard IEC 62832 "Digital Factory" serves as a template for the description of assets in the administration shell (see above). IEC 62832 is divided into three parts and defines a framework for using dictionary entries (e.g. classes and properties) to describe asset types and to describe specific assets. It thus offers an internationally binding basis for the use of properties, both for conventional engineering and for smart manufacturing.

These descriptions can include functional requirements for assets, properties of assets, variable data, assignment of functional requirements to specific assets, and structural composition and other relationships between assets. The standard considers all phases of the asset life cycle, i.e. design, construction, commissioning, operation, maintenance and dismantling.

Specific assets ("PS Asset", real or logical objects) are described by asset descriptions ("DF Asset", virtual representation) (see Figrue 16). Types of assets are modelled by asset classes and thus represent one or more assets that share the same set of properties (e.g. product types). If the described assets have a modular structure, the corresponding asset descriptions (or asset classes) can also describe a modular structure. Relationships between specific assets are represented by asset links. Data elements can be used to describe static properties or variable data of assets. Through this structure, the standards series on the Digital Factory lays down important principles for Industrie 4.0-systems. Consistency with the description of the administration shell is an important prerequisite for a consistent description [see RE 2.3-3].



Figrue 16: Digital Factory and DF assets describe product systems and PS assets

IEC 62832 defines data types that support such descriptions. The meaning of the concrete data (e.g. product description, module description, interface description, function description) is derived from the underlying dictionary entries. These dictionary entries can be defined in dictionaries (such as the common data dictionaries, CDD or CDP of eCl@ss e. V.), as in IEC 61360 or ISO 22745.

Characteristics and semantic properties

The scope and level of detail of the characteristic determine how exactly an asset is described. The term "property" has become established for characteristics with a standardized description. With the specification of the administration shell there is a specification that consistently focuses on the use of properties for information modelling. For the description of products, means of production, components and individual parts as a basis for the implementation of Industrie 4.0, production units must be enabled to transmit standardized properties combined with standardized transmission formats. This makes it possible for receiving systems to understand the data correctly and use it in subsequent processes such as purchase orders, production orders and maintenance notes. This concept is also referred to as "semantic interoperability".

Considering a property in detail, it also has characteristics, such as a data type and a default value. To distinguish between the property of an asset and the characteristic(s) of that property, the latter is referred to as an attribute (see **Chapter 2.6.1**). Properties and their attributes form the basis for integration and interoperability. Each individual property is named and compiled with its attributes as data. These properties are used in various engineering phases in corresponding system models. The present standardization roadmap goes into more detail on modelling and the use of properties in further chapters, in particular on the subject of integration (see **Chapter 2.5**). Currently, properties have already become well established in the purchasing process and the first fields of application can be identified in engineering.

In the future, properties will be used throughout the entire life cycle This results in an extension of the device and component classes, which are described by means of standardized characteristics and properties in eCl@ss and IEC CDD. There are also device classes, e.g. drives and pumps, which provide OPC UA Companion Standards with properties [see RE 2.3-4].

The use of properties in operative phases of the life cycle makes it clear that additional properties are important for individual assets (e.g. serial number) and have to be included for planning documents [see RE 2.3-5]. Characteristics are also required that change dynamically in the asset depending on its interaction with the machine or system [see RE 2.3-6, RE 2.4-1].

This means that further characteristic properties, such as time stamps and validity statements of the value are important. DIN SPEC 92000 (Property Value Statements) shows a promising path for this [see RE 2.3-7].

IEC 62832 supports the description of functional requirements. It is already commonly used in the area of process equipment (OLOP in IEC 61987) but has so far been ignored in other areas [see RE 2.3-9]. In this roadmap, properties are discussed in more detail, e.g. in Chapter 3.4.

The special position of properties in I 4.0-systems is also evident from the numerous projects and activities for the further development of the use and methodology of properties, from which future requirements and trends can be derived. In the project "Semantic Alliance for I 4.0 – SemAnz40" funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), it was shown how features can be used to form a suitable semantic basis for the exchange of information in the use cases of Industrie 4.0 [30]. Further activities are, for example, the VDMA guideline "Interoperability through standardized features" [24] of the Working Group NA 060-30-04-05 "Product characteristics and libraries", and the activities on NAMUR Open Architecture and the ZVEI activity on Drive 4.0 [31].

Data is transferred, processed, combined, aggregated, evaluated and interpreted in Industrie 4.0-systems. In such systems, decisions are automatically made and actions controlled on the basis of the data available in the system and the information gained from it. Consequently, the quality and trustworthiness of the stored and entered data are of utmost importance (see Chapter 3.4).

With regard to proper and professional data interpretation and further use in Industrie 4.0-systems, essential context information on each data point is indispensable [see RE 2.3-10]. The aim is to define a standardized structure, table of contents and input mask on the basis of the above and other criteria and information requirements. It follows from the diversity of the data that not all "information fields" can or must be filled in, but minimum standards should be set. The aspect of a "legitimate interest in the data" regulates the access rights to the data details or context information.

Geometric Product Specification

For the implementation of Industrie 4.0-concepts it is necessary to define and label the requirements for the products precisely, completely and clearly. Against this background, the ISO system for **"Product specification and verification" (GPS)** was developed, which is not to be confused with the Global Positioning System (also GPS). The principles are described in ISO 14638. The ISO system was developed to describe standards for the manufacturing of products, which refer as far as possible to GPS symbols in drawings/models.

Digital Nameplate

For the linking of the physical objects and their digital images, a robust, unambiguous identification is absolutely necessary. Traditional machine-readable markings consisting of several data elements and control characters from the field of "non-printable ASCII characters" such as FNC1 or RS, GS and EOT are too complex for this, are only partially unique and do not provide a direct link to the Internet. DIN SPEC 91406 describes an approach that solves this challenge with a unique URL in a concisely recognizable QR code. However, this radical simplification is revolutionary in the body of standards and, in addition to the internationalization of DIN SPEC 91406 as such, also requires adaptations to almost all application standards for machine-readable marking.

Due to special requirements in explosion protection, the expert committee DKE/K 241 pushed ahead with the standardization of an electronic type plate and published the preliminary standard DIN VDE V 0170-100 as a draft. The concepts developed are universally applicable and can therefore be transferred and extended to practically all branches of industry [see RE 2.3-11, RE 2.3-12].

System life cycle, life cycle record

In production as well as in the entire life cycle of products, technical equipment and entire production systems, much data accumulates that can be made usable. Ideally, the entire life cycle data of technical plant and all Industrie 4.0-components are collected in the same form in administration shells and made available throughout the entire life cycle (with specific access rights). The contents are differentiated into type and instance life cycle data.

The developments and definitions of the life cycle record address, among other things, current challenges:

- → for continuous engineering [25],
- → for use,
- → for maintenance, repair, reconstruction and conversion,
- → for proper disposal.

DIN 77005-1 "Life cycle record for technical objects" specifies how information on plants and their parts is managed in a structured manner. Various types of life cycle record are available for this purpose, which are structured hierarchically. Metadata helps users to assign responsibilities, search for information and define relationships between information. An application method ensures that life cycle records are uniformly managed, always up-to-date and complete. Life cycle records according to DIN 77005-1 are self-explanatory and thus understandable for all parties involved in all phases of the life cycle. They can serve as a basis for life cycle records for all Industrie 4.0-components.

Part 1 of the DIN 77005 series is deliberately technologically neutral. The basic principle of life cycle records is also possible and useful without the extensive use of ICT. However, the added value of the described structures and methods can be tapped primarily through the use of modern ICT.

In the following, a digital life cycle record is understood to be a holistic information technology support for the implementation of the requirements in DIN 77005-1. It implements an interdisciplinary information space in which all information about the plant and its parts is temporally summarized and structured. The structuring of this information space is based on a model. The life cycle record model is based on a series of models from standardization.

Important models to be integrated include those described in IEC 82045-2, IEC/TS 62771, W3C SOSA and IEC 62507. The life cycle record model must also consistently reflect the separation between type and instance and the various life cycle models introduced in IEC 62890 for life cycle management. The structure of the object must be reproduced in a chronologically comprehensible manner, including the various aspects according to IEC 81346. All information must be linked to the object and/or its parts.

The life cycle record and the administration shell for I 4.0-components pursue basically the same objectives and share a broad normative basis. The life cycle record is therefore suitable for inclusion in the standardization work on Industrie 4.0 as a sub-model of the administration shell. The model of the life cycle record goes far beyond the already published administration shell model in VDI 2770. Questions regarding the integration of the operational context and the plant context are still to be discussed.

Besides the integration and aggregation of information, the digital life cycle record ensures the long-term availability of this data. Data integration must be robust enough to meet the requirements for long-term storage of information.

In the work on the life cycle record, the focus is on humans with their individual information and decision-making needs. Views of life cycle records and the information they contain are of particular importance in this respect. Views also help humans evaluate information in relation to their role-specific context and support the introduction of necessary measures by linking background knowledge. These extended approaches should be transferred to I 4.0-components and their administration shells [see RE 2.3-13]. Accordingly, the digital life cycle record helps the actors to evaluate information and (automatically made) decisions in summary form and to correct them if necessary. The structure of the life cycle record ensures continuous traceability.

Maintainability

An important characteristic of a technical system is how well its maintenance is enabled and supported. This is referred to as "maintainability". The resulting requirements, such as the possibility of fault diagnosis and preventive maintenance, the interchangeability of components, modularity, etc., must be taken into account right from the planning and design phase of technical systems.

Basic aspects of maintainability are described in DIN EN 60300-3-10:2015-01. In particular, the vertical and horizontal integration of systems results in new solutions in Industrie 4.0 that require these aspects to be supplemented. A common understanding of all parties involved in the maintenance process of Industrie 4.0 plants will be promoted by further basic standards on maintenance. In the European committee CEN/TC 319 "Maintenance", various working groups, etc. are currently working on standards for "Maintenance Management" and "Maintenance Engineering". These standards are intended to concretize and standardize basic tasks, role definitions and methods in the maintenance process of Industrie 4.0 installations [see **RE 2.3-14**].

Another aspect of the maintainability of Industrie 4.0-systems is the consideration of the different life cycles of the respective subsystems. Obsolescence of a subsystem must not lead to obsolescence of the integrated overall system, otherwise the maintainability of the overall system is no longer possible. Standards for I 4.0-systems should therefore also be drafted with this aspect in mind [see **RE 2.3-19**].

DIN EN 62402-09 sets out requirements governing obsolescence management of objects and deals with all types of objects, the availability of which may come to an end during the life cycle of the product. Obsolescence management should therefore be taken into account when Industrie 4.0 installations and products are first being conceived and developed [see **RE 2.3-17**].

The maintenance of I 4.0-systems will basically be characterized by intensive interaction between different service providers for maintenance (manufacturer, operator, industrial service) (see **Figure 17**).

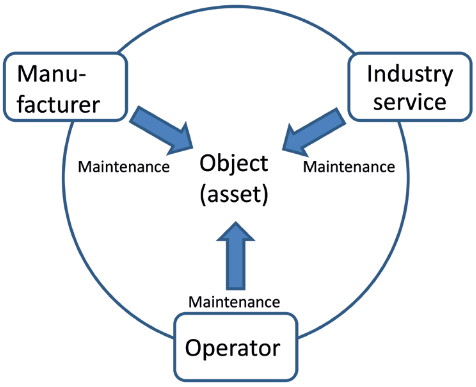


Figure 17: Interaction between different service providers for maintenance (manufacturer, operator, in-dustrial service)

The basis for this interaction is a common "language" of the respective components and actors. Such a common "language" is based, among other things, on a uniform understanding of terms and coordinated processes for maintenance. Non plant-specific basic standards for maintenance will provide the foundation for specialist or sector-specific standards governing aspects specific to maintenance. DIN EN 13306: 2018-02 provides a uniform definition of the basic terms for all types of maintenance and maintenance management, regardless of the type of objects and maintenance actors involved [see **RE 2.3-15**].

The essential processes of a comprehensive maintenance organization with their interrelationships are described in detail in DIN EN 17007**,** thus ensuring a uniform understanding of the processes of all those involved in maintenance [see **RE 2.3-16**].

DIN EN 16646 on maintenance within asset management shows the understanding of roles and thus also the key position of maintenance in the life cycle of an I 4.0-plant.

Reactive and periodic preventive maintenance strategies will in future be replaced more and more by predictive maintenance strategies. In the future, intelligent and networked I 4.0-systems will detect a large part of their potential faults before they occur. The basis for this is provided by condition monitoring technologies, in which data from a plant is recorded and evaluated as comprehensively as possible using appropriate sensor technology. The normative basis for condition monitoring is ISO 13374 on condition monitoring and diagnostics of machines during the processing, exchange and presentation of data. Furthermore, ISO 13381 describes the principles for prognosis in the context of condition monitoring and diagnostics of machines.

Another current focus of standardization is the documentation and exchange of maintenance-relevant data and information over the entire life cycle of a system, so that this data and information is also available and can be used across companies (see Section System Life Cycle).

The iiRDS standard (intelligent information Request and Delivery Standard) developed by tekom, the trade and professional association for technical communication, enables the provision of intelligent maintenance-relevant information independent of industries and manufacturers. Manufacturers can provide customers with the required usage information in a standardized way, while customers can integrate information from various manufacturers into their systems in a standardized manner. This is achieved by the underlying standardized metadata, which makes content semantically accessible.

One goal of the iiRDS consortium, founded in 2018, is the specification of standardized mechanisms and a standardized vocabulary, which, in the context of Industrie 4.0, make it possible to generate situation-specific and context-specific information for the cases occurring throughout the product life cycle. Although often only humans are mentioned as recipients, the mechanisms are also required for information between machines. The following functions, among others, are to be fulfilled in accordance with Industrie 4.0 [32]:
→ dynamically adapt to the user and application context
→ provide targeted information for all life cycle phases, from specification to maintenance
→ match the delivered system, even after configuration changes and updates
→ dynamically integrate assistance and sensor information and operating parameters
→ support various search and filter functions.

The metadata of the iiRDS thus represent a standardised *vocabulary* for technical documentation [see RE 2.3-18]. The iiRDS consortium is currently cooperating with the committee responsible for VDI 2770 to ensure the compatibility of that guideline [see RE 2.3-19].

Predictive maintenance is another current standardization focus on maintainability. Within the German-Chinese Standardization Cooperation Commission (DCKN) in 2019 an update to the "Standardization Roadmap of Predictive Maintenance for Sino-German Industrie 4.0" was developed in which the principles of predictive maintenance standardization are described. Central content was included in the project IEC 63270 ED1 "Industrial automation equipment and systems – Predictive maintenance" within IEC/SC 65E [see RE 2.3-20].

In the field of predictive maintenance, it is also important to consider how the actions of human actors are taken into account in such a system. Thus, in the case of condition monitoring of installations, it is basically important that changes in the behaviour of the installation can be traced back to the respective cause. For this purpose, manual actions such as oil changes must also be communicated to the system in an up-to-date manner as possible. The guideline VDI/VDE 3711 Part 1 on "Input and Transmission of Maintenance Information for Condition Monitoring – Digitization of Offline Information", developed in recent months, standardizes the interface between human actors and condition monitoring systems and must also be considered in approaches to predictive maintenance. The scope of VDI/VDE 3711 Part 1 extends from the system manufacturers of condition monitoring software and data analysis tools to the system manufacturers and the customer/user. In order to internationalize VDI/VDE 3711 Part 1, it is currently being examined whether it can be submitted to the IEC as a project proposal via the committee DKE/K 931 "System aspects of automation" [see RE 2.3-21].

Validation and testing

Formal description methods serve to increase efficiency and to observe economic principles when creating standards, test specifications and methods. ETSI TC MTS has further developed the test language "TTCN-3" with object-oriented features, Conformance Test Sites, Test Description Language (TDL), to the Test Purpose Language (TPLan). Test procedures are defined and classified as "Conformance", "Interoperability", "Security" and "Performance" (CISP) tests. This provides an operational tool (testing platform) for the CISP testing variants. CISP also represents verifiable properties (morphisms), as already described in the semiotic context defined above. Test procedures can be written for each CISP morphism that can be applied to the I 4.0-component both in the information world (see Chapter 2.6.2), and in the physical world (asset).

At best, CISP tests find many errors that can be corrected; however, successful tests are not proof of the absence of errors, which is reserved for verification with formal methods. In principle, testing is a form of validation, because under certain assumptions and conditions, a series of tests can be carried out with which the assumptions can be verified as false or correct, i.e. validated. Validation works just as well, if not better, with a semantic tool for model simulation.

Technical Committee TC "Methods for Testing and Specification – Testing Working Group (MTS – TST WG)" in ETSI is developing guidelines, test catalogues and test specifications for IC technologies [33]. For this purpose, the TST working group uses the knowledge gained from test development languages and methods already in use. [see RE 2.3-22].

The latest technological developments in the IoT application area are taken into account by writing and recommending test procedures, based on the network layer, for communication protocols, for the evaluation of connectivity between connected systems (nodes), for IT security and for performance. Currently, test specifications and recommendations for MQTT, CoAP, LoRaWAN as well as a catalogue for security test objectives of a profile derived from IEC 62443 are being developed. The current development and status are available at the ETSI Portal [34].

ETSI MTS/TST has links with other standardization organizations such as ETSI TC SmartM2M, oneM2M, AIOTI, IETF, ISO/IEC JTC1/WG10, ISA, OASIS, OPC Foundation, OMA, Eclipse etc. Furthermore, TC MTS/TST works very closely with the ETSI Centre for Testing and Interoperability (CTI) [35]. CTI also supports the test developments of oneM2M and for Intelligent Transport Systems (ITS).

Environmental simulation/Product qualification

Environmental simulation is an engineering discipline with a broad and interdisciplinary approach. It is an essential tool for improving and evaluating the quality of products and, as a building block in the product development process, can make a significant contribution to resource efficiency and the sustainability of a product in the individual stages of its life (life cycle engineering). It comprises the following steps:

→ measurement and evaluation of environmental influences,
→ simulation of environmental effects under controlled boundary conditions, both in the laboratory and virtually,
→ assessment of the effects of the environment on an object
→ assessment of the effects of an object on the environment.

The procedure and the requirements for the methodology of a product test are defined and explained in DIN EN 60068-2, for example.

Environmental simulation is a systematic technology and methodology tool to collect and evaluate data related to the functionality and lifetime of products, taking into account all relevant environmental influences. Environmental simulations are carried out by the *Gesellschaft für Umweltsimulation GUS e. V.* (Society for Environmental Simulation) [26].

In a research project initiated by the *Gesellschaft für Umweltsimulation* it was shown that it is possible to numerically investigate and predict the lifetime of products depending on environmental influences. Two things are necessary for this: on the one hand, the environmental influences must be recorded digitally, which is possible to a large extent, as these are mostly of a physical or chemical nature. On the other hand, the effect of these influences on the products, or directly on the materials on which they are based, must be recorded, quantified and put into a digital format. Recording and quantification is already the subject of environmental simulation with mature methodology and experience. The challenge of product qualification in Industrie 4.0 will be to put the effects of the environment into a digital form in such a way that they can be integrated into already existing simulation procedures, in order to be able to create a comprehensive digital image of environmental effects in the administration shell.

Environmental sensors and data

Sustainability and resource efficiency are part of the Guidelines 2030 for Industrie 4.0 [1]. In order to investigate the effects of the environment on an industrial production or on materials or goods in a logistics chain or vice versa, the effects of industrial production on the environment, the use of appropriate environmental sensor technology (e.g. humidity, temperature, emissions, UV radiation, multispectral images) is necessary. Such environmental sensors usually provide environmental sensor data with time and location reference, which can be displayed in time series and maps (also combined). These are then merged with production and quality inspection data from industrial production and logistics.

Another research project on environmental data in Industrie 4.0 of the German Federal Environmental Agency (UBA) focuses on data from industrial companies and closely related processes. Environmental data is systematized and checked for availability and data formats. Obstacles are identified with regard to full interoperability and traceability, and solutions are tested in operational practice. In addition to recommendations for policy and practical implementation in companies, the project results are expected to include concrete recommendations for standardization for 2021. The recommendations for action of the Standardization Roadmap I 4.0 Version 3 are being addressed, further developed and concretized with this project.

Here, standardization is faced with the challenging question of the right process recommendations, i.e. how they can be made interoperable for Industrie 4.0-systems.

Industrial Cloud Platforms
In the area of "Industrial Cloud Platforms", Industrie 4.0 focuses on standardized IT landscapes and supports the networking of I 4.0-components both within the company (vertical integration) and across company boundaries (horizontal integration). Against this background, more and more companies are setting themselves the goal of replacing their current technical systems with cloud-enabled solutions and thus introducing new IT architectures in the company.

Vertical integration is achieved through the interaction of various processes at different company levels, as shown in the automation pyramid (see **Figure 18**). Industrie 4.0 requires the dissolution of such immovable hierarchies that have grown historically over the last decades. This is done with the main underlying goal to achieve a continuous networking of all production systems, processes and services in a company, from the field level to the company level. Cloud platforms are likely to play a decisive role in the future, as they provide the necessary tools to implement a rapid migration to flexible IT architectures.

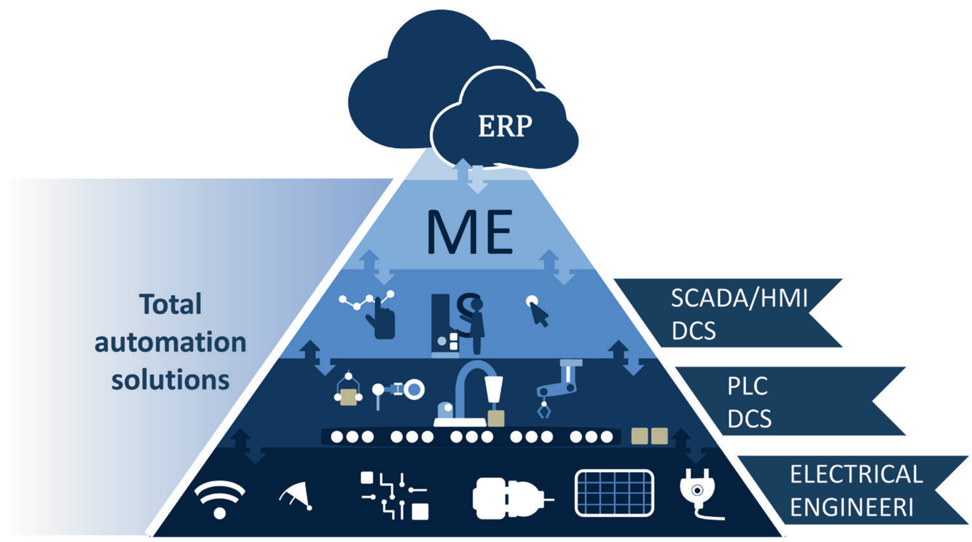


Figure 18: Automation pyramid

The migration of current server-oriented solutions to cloud solutions requires that application programs run in the cloud that previously ran "on site" in stored program controls. For this purpose, back-end processes with "real-time requirements", storage and interfaces must be developed that are tailored to the operational platform of the cloud. The conditions existing in the industrial environment must be met. At this point it is important to mention that the standardization of the above-mentioned concepts has received very good practical support over the last years, both from national, European and international SDOs, industry associations and research projects, which have provided a practical environment for the developed standards (such as LNI 4.0).

Industrial cloud platforms are already actively used in production [36]. They can be based on several technologies and concepts and combine several standards (cloud computing, edge computing, IoT, security, etc.). If a manufacturer wants to network their products and offer or use digital services, they can currently choose from more than 500 commercial offers. Companies need a dynamic, flexible and standardized cloud IT infrastructure in order to be faster than the competition. Because when companies integrate standard technologies and processes into their IT architecture, they have several advantages, such as faster deployment of IT systems and applications, compatibility through the use of proven standards and reduction of errors.

In Industrie 4.0 a company's cloud IT architectures should be based on standards and reference architecture models (e.g. RAMI 4.0, IDSA-RAM, IIRA). Depending on the respective requirements of the IT architecture and the framework on which the company bases its business models, appropriate standards should be used in a targeted manner.

Appropriate interoperability standards should efficiently support the exchange of data and allow seamless integration between the components. To achieve this, ICT and OT technologies must be largely harmonized. There is currently a need for an open and distributed, real-time and secure operating system for production that combines the above technologies on the basis of standards, as shown in [38]. There should be an open IT backbone with standardized interfaces for the versatile automation of the factory of the future as the basis for an ecosystem, including data-driven services for artificial intelligence. For this purpose, a flexible and expandable architecture can be standardized for future requirements ranging from the cloud, edge technology, up to the shop floor into the machine for real-time applications [see RE 2.3-23].

2.3.2 Recommendations for action and application

2.3-1 Use and standardize the administration shell concept consistently

To support the processes described above, such as maintenance functions and storage of knowledge in a life cycle record, the assets must be able to exchange data with production systems and plant operators via standardized interfaces with standardized semantics. This is achieved via the administration shell concept, if the administration shells or their sub- models, as well as their communication between I 4.0-components are defined in standards (see Chapter 2.5.1). It is recommended to support and advance the activities in IEC/TC65 WG 24 IEC 63278-1 ED1 "Asset administration shell for industrial applications – Part 1: Administration shell structure".

2.3-2 Internationalization of further parts of the standards series on the administration shell
It is proposed that the approach to the further structure of the series of standards should be based nationally on the work of the Platform Industrie 4.0/AG 1. In this context, attention is also drawn to coordination with the activities of IEC/TC65/JWG 21 TF 8 "Digital Twin and Asset Administration Shell" and IEC/TC 65/WG 24. **RE 2.3-15** below discusses the digital life cycle file according to the elaborations of DIN 77005-1.

2.3-3 Digital factory
Testing the consistency of IEC TS 62832-1 and administration shell IEC 63278-1 ED1 "Asset administration shell for industrial applications – Part 1: Administration shell structure", as well as the other planned parts of the standard with the standardization activities concerning the administration shell in IEC/TC65 WG 24.

Characteristics and properties
2.3-4 Existing fieldbus profiles, companion specification and other specifications that define device and component properties should be transferred into standardized dictionaries, such as eCl@ss and IEC CDD. Furthermore, they should be presentable in a suitable semantic way (e.g. graphic/algebraic).

2.3-5 Characteristics of conceptual assets, such as planning documents, should be included in standardized dictionaries such as IEC SC 3D, e.g. the specifications in VDI 2770. Additionally, planning documents should be communicable between humans and machines/I 4.0-components.

2.3-6 Prerequisites must be created that, in addition to master data, parameters and state variables can also be included in standardized dictionaries. This also applies to the use of semantic methods that relate to the representation and analysis of properties.

2.3-7 Extended instance-related attributes must be covered by standards. A transfer of DIN SPEC 92000 into the IEC 61360 series is suitable for this, for example.

2.3-8 Preparatory activities for the standardization of sub-models of the administration shell are to be initiated. The integration should take place in coordination with IEC/TC 65/WG 24. A sub-model must be standardized in its basic features, which means that there must be both basic/obligatory properties and basic/obligatory functions that can be supplemented by an Industrie 4.0 partner with individual properties and functions. This means that, for example for energy considerations, the same obligatory property and functions must be available for different assets, so that, for example, all components of a system or systems of a plant can be easily consolidated or controlled in the same way. Specific amendments remain possible.

2.3-9 Conditions must be created so that functional requirements (e.g. role and expected function) and their fulfilment (e.g. supported role, provided function) can be included in standardized dictionaries so that the execution of production processes by production systems can be planned.

2.3-10 A standardized structure with basic, essential and contextual information should accompany all data integrated into Industrie 4.0-systems and should contain clear minimum requirements for integration. The definition of the structure and minimum requirements should be standardized. The necessary, systematic linkage with the models must be considered.

The following information should be the content of a "data profile", which is "supplied" in a standardized form with data integrated into the system. The "data profile" can be designed as a sub-model of the administration shell.

- → A precise description as possible of the information content of the data, information on the precision of the data, indication of the units, periods of time, etc. in which the respective numerical values are displayed by default (e.g. kilogram, EURO, per year)
- → A precise description as possible of how the numerical value was determined and how many individual data it is based on, a description (characteristics and properties) of the measurement technology, the recording and calculation methods used
- → Documentation of the geographical location of the data source with exact position and time e.g. in a production process
- → Documentation of the legal areas affected by the data (e.g. product, environmental, waste law) with concrete legal and administrative regulations at national, EU and international level that are directly related to the data (e.g. EU industrial emissions directive, REACH, UN climate agreement)
- → Definition of defined, legally anchored access rights for those who have a legitimate interest in the data (e.g. state, authority, company, manufacturer, consumer)
- → Documentation of the owner of the data, and any additional contact person for further information on the data

Digital Nameplate

2.3-11 The approaches for a Digital Nameplate as in DIN SPEC 91406 (according to the PAS method) and VDE V 0170-100 are to be continued and implemented internationally in a suitable form.

2.3-12 Adaptations in all application standards for machine-readable marking along the lines of DIN VDE V 0170-100 together with DIN SPEC 91406

System life cycle, life cycle record

2.3-13 The model for the digital life cycle record based on DIN 77005-1 is to be regarded as a sub-model of the AAS (Asset Administration Shell). The specification of the AAS metamodel, available since the end of 2018, provides the necessary basis for this. It is recommended that the sub-model for the life cycle record be further elaborated and supported by the international standardization work on the administration shell within IEC/TC65 WG 24 (see RE 2.3-1, RE 2.3-2).

Maintainability

2.3-14 Consideration of maintenance aspects both from the point of view of the manufacturer and the operator or user, also and in particular with regard to standards on predictive maintenance

2.3-15 Use of uniform maintenance terminology compliant with DIN EN 13306:2018-02 in all standards in which maintenance aspects are included

2.3-16 Consideration of harmonized process interfaces as in **DIN EN 17007:2018** in all standards with process specifications on maintenance

2.3-17 Evaluation of all stipulations governing Industrie 4.0-solutions in terms of controllability of possible risks of obsolescence as in **DIN EN 62402-09**.

2.3-18 Standardization of the interfaces of I 4.0-components (plants and products) for the input of current maintenance information, e.g. on the basis of iiRDS (repairs, maintenance, conversions) into the systems of condition monitoring and predictive maintenance.

2.3-19 Investigation into the internationalization of **VDI 2770 Part 1** on minimum requirements for digital manufacturer information

2.3-20 Active participation of German experts in the standardization project IEC 63270 ED1 "Industrial Automation Equipment and Systems – Predictive maintenance" with Chinese coordination

2.3-21 Internationalization of **VDI/VDE 3711 Part 1** "Input and transmission of maintenance information for condition monitoring – Digitalization of offline information". A timely examination of the internationalization efforts is to be carried out by the national mirror committee DKE/K 931.

Validation and testing

2.3-22 Operational models and appropriate tools are needed for a simulation. Tools and models need common semantics for machine execution and for a comprehensible representation of the characteristics of the considered system in its environment.

Industrial cloud platforms

2.3-23 Open, distributed, real-time and secure operating system

Standardization activities for a flexible and extensible architecture for future requirements of cognitive services, real-time applications and data marketplaces should be taken up in the relevant committees. Hybrid cloud platforms, IIoT applications and cyber-physical architectures should be investigated as core elements. Uniform life cycle management of all IT resources, means of production and technical building equipment are just as much a part of this as the creation of an integrated infrastructure for real-time capable, cross-domain value-added networks for the AI-supported, autonomous production of the future.

2.4 Interoperability

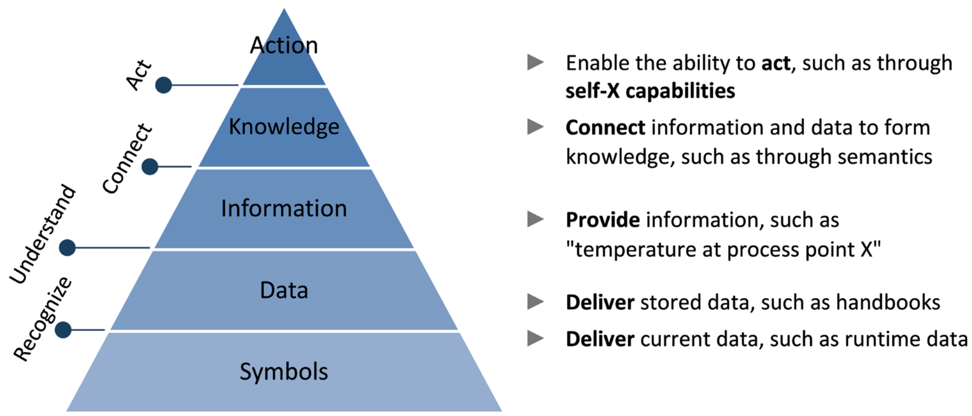
2.4.1 Status and progress since Version 3

In the case of networked production, all actors in a dynamic and open ecosystem must agree among themselves on the objectives to be pursued and the corresponding concepts in a mutual exchange of information and knowledge. Such complex, decentralized structures must be designed to meet the needs of I 4.0-compliant communication and ultimately enable seamless cooperation [74] between all actors involved [75] – this is referred to as interoperability. One example is **Use Case 2** in **Chapter 1.4.1**.

Here, various machine tools exchange information about their respective current production capabilities, which are to be evaluated in the context of I 4.0-production networks and production orders. Complex information from different (sub)systems of a machine tool must be provided, processed and interpreted. The interactions between the administration shells of the participating (sub-)systems (or I 4.0-components) orchestrate the I 4.0-system to implement the value chains [76] of an ecosystem. For this purpose, the administration shells need a common language in order to achieve a high degree of interoperability in the storage, exchange and processing of information in such a technical system at the information level.

On the basis of IEC PAS 63088 and the structure of the administration shell, this common language was developed using interaction patterns consisting of semantically well-defined messages and defined in the guidelines VDI/VDE 2193 **Parts 1 and 2** [see **RE 2.4-5**].

The knowledge pyramid according to Fuchs-Kittowski (**Figrue 19**) can be used as a basic paradigm for the structured representation of knowledge creation. The system can provide and process in cooperation not only data (syntax) as raw material, but also information and knowledge. Therefore it is important to provide meanings and contextual information.



Figrue 19: Knowledge pyramid according to Fuchs-Kittowski (Source: [19]).

The data to be exchanged must mean the same to all communication partners in the context of machine-to-machine communications and machine-to-human communications. This is achieved when
- → (1) a common vocabulary is used (properties model),
- → (2) the context in which the individual terms are used is known (information models),
- → (3) agreed formation rules for rates for message exchange (formation rules for messages) are observed, and
- → (4) the sequence of the exchange of vocabulary or sentences can be interpreted in the intended way (interaction models) [77].

From the networking of information (semantics), knowledge (pragmatics) can then emerge, from which automated and continuously optimizing actions (action or decision) can be derived. How the information is linked to logical relations is determined by ontologies. These should explicitly specify the formal origin of individual terms in order to represent knowledge in the respective context.

Interoperability is the key component for smooth communication and seamless integration between actors and therefore plays a special role in standardization, as explained in detail below [74, 75].

Data models

Data is stored in database systems, which are mainly classified according to the data model used. While data are objects, "information" is created by observation and is therefore closely related to the concept of "event". An event is e.g. the toss of a coin with the possible results "heads" or "tails". The information "H OR T" is obtained from the random position of the coin resulting from the toss, whereby "H", "T" are representations, i.e. data elements from the alphabet of the coin toss. In communications engineering, "H" and "T" are messages that are for communication between a sender (the coin) and a receiver (the observer). It is therefore useful to distinguish between coding, data and information. This principle of differentiation can also be maintained at a "higher level of communication". Data and information can be typed or combined into a data pattern model. Data type models and data pattern models can be used to analyse system states or to test interoperability between system components using expert knowledge.

Semantics

Semantics is the study of the meaning of signs. In the semiotic triangle (see Figure 20) it is shown as the relationship between the descriptive ontological domain and the semantic explanatory domain. In general terms, this field of knowledge deals with the description of words, signs (e.g. emojis, traffic signs), strings of signs, sentences and other forms of representation of things of interest.

If systems are to cooperate with other systems and exchange information, they must understand each other. The information must therefore follow a uniform semantics. This applies to machines that independently (re)distribute production orders among themselves, as well as to sensor data that are collected from different measurements. But what exactly is "semantics"? Semantics is concerned with the relationship between symbols and their meaning. A symbol can be a graphic character (such as a traffic sign) or an alphanumeric unit (such as a word) that names a thing. The thing – the object of observation – is thereby a real or a conceptual object that is to be determined semantically. This thing is described by a term – the definition. The thing is identified by a name (with a symbol). At the same time the description of the thing (the term) is referenced, which explains what is meant. The relationship between name, term and thing is described in the "semiotic triangle". The things belong to the real world. Symbols and definitions of terms are components of the information world.

Semantics is therefore required when two or more partners (e.g. sender and receiver) exchange information. Without common semantics, signals would be present, but the partners could not understand their meaning. People work together on tasks. They communicate with words (symbols). They understand each other when they have the same terms (definitions) for the designations used. So they have agreed on a semantics of the things they talk about.

In human-machine communication, humans and machines face each other as senders and receivers. Machines process data, humans think in terms. In order for them to understand each other, the semantics of the machine must correspond to the concepts of the human being. Machines use symbols without understanding their meaning. Since the machines are designed by humans, the symbols can be assigned the appropriate meaning. To achieve this, the developer must start from the same understanding of terms as the users when programming the machine software and provide the users with the correct names for the terms to be communicated.

Machine-to-machine communication requires that both sides understand each other both syntactically (composition of elementary symbols) and semantically (description of meaning). There must be a clear agreement on the interpretation of the data on both sides. This agreement is achieved if the data is enriched with additional descriptions, sometimes in the form of machine-readable data. Data thus becomes information.

Information models

In a mathematical-algebraic sense, an information model is a composite Abstract Data Type (ADT) with several basic sets (types), variables and axioms, rules and functions between types. It therefore represents the meaning of compound data as an abstract data type (mathematically: term algebra), whereby only that part of the meaning is contained in the model which has also been included in the description. In a digitally available information model with a textual form of the model that can be understood by humans, it would be difficult for a machine to interpret it. A mathematical form is understandable, i.e. interpretable, for both the machine and the human. Therefore a mathematical form of the information model, e.g. as ADT, is preferable.

Instructions for creating information models are manifold and range from glossaries and thesauri to object-oriented classifications (e.g. AutomationML), to models based on formal logic (e.g. ontologies) and semantic representations. The information models form a bridge between semi-formal or formal models and the linguistic representation of semantics, i.e. morphisms in the semiotic triangle (see Chapter 2.5.2). Finally, semantics forms a basis for achieving interoperability between systems in heterogeneous contexts.

An information model is a set of data object types and their dependency relationships, which are all together described as ADT, defining their mathematical-algebraic meaning. An information model is then equal to its semantic data model. A large number of information models have already been created. Striking examples are fieldbus profiles (definition of parameters and behaviour of measuring and control devices with industrial communication connection), OPC UA Companion Specifications, but also abstract models such as EDDL (Electronic Device Description Language) and AutomationML, which provide a description tool for information models. From the point of view of semantics, domain knowledge has been transferred into information models and this represents an important contribution to interoperability.

Ontologies

As a formal means of establishing interoperability between information systems, ontologies describe central entities and aspects as comprehensive information models Therefore, different actors are dedicated to providing ontologies for different application areas and purposes.

The mentioned "logical relations" of an ontology are "entity-relationship" structures, which in turn can be represented as "node-edges" data structures in a graph. On the other hand, graphs are also used for the interoperability of processes, so that both process and data structures can be represented in the same way, as a graph. The "logical relations" of the ontological data structures thus receive a simulation-capable graph manipulation semantics through the dynamization of the static graph structures, i.e. the insertion of directed edges. Both ontologies and processing networks can be validated with suitable tools [see RE 2.4-2].

Terminology
The VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA) and the VDMA accompany and support their members on the way to Industrie 4.0 and have been working for some years now to develop the terms relevant to Industrie 4.0. Thus, in connection with the topic of Industrie 4.0, many terms have already emerged, e.g. I 4.0-component, I 4.0-system, or I 4.0-platform.

In the VDI status report "Industrie 4.0 Terms" (April 2017), non-technical terms that are little used in the technical environment of automation, such as ecosystem and value creation network, were also formulated [78].

2.4.2 Current developments

Current trends in standardization with regard to interoperability address further challenges, such as semantic interoperability and expression of meaning, application of semantic networks and data lakes for mapping information from the entire data set, development of standardized mechanisms and tools for translating interoperability into technically usable artefacts, and standardization of new terms in the context of Industrie 4.0.

Semantic interoperability
The White Paper "Semantic interoperability – Challenges in the digital transformation age" [80] was developed by the MSB (Marketing Strategic Board) of the IEC. This white paper provides an assessment of current and future challenges related to semantic interoperability in industry sectors and related industry-specific standards.

The main objective of the paper is to identify conditions under which the application of semantic technologies, together with existing information models, can be used to improve interoperability within and between applications and domains, and to formulate recommendations based on a review of use cases compared to existing technologies and standards.

Semantic interoperability affects the entire information life cycle, both horizontally between devices and systems and vertically across different systems. Therefore, the content of this white paper is aimed at a broad audience:
- (1) IEC decision-makers;
- (2) Managers charged with the decision to provide resources for information modelling/knowledge representation;
- (3) Persons responsible for the life cycle management of products and systems;
- (4) Ontology developers and semantic technologists;
- (5) Engineers involved in the development of standards-based semantic interoperability in tools.

IoT interoperability
The international body ISO/IEC JTC 1/SC 41 deals with horizontal aspects of the Internet of Things (IoT). The ISO/IEC 21823 series of standards is intended to establish a common understanding of interoperability. The objective of ISO/IEC 21823-1 is to develop technical systems in a framework in such a way that they are able to exchange information and use it efficiently with each other. Further drafts from the series are currently being developed: ISO/IEC 21823-2 [82] on interoperability and transport mechanisms and compatibility of the communication infrastructure, and ISO/IEC 21823-4 on syntactic interoperability, including ontologies, data formats and more.

In particular ISO/IEC 21823-3 [83] defines semantic interoperability as the ability to understand data shared by systems at the level of fully defined domain concepts (see ISO 18308-1). This specification specifies an ontology-driven approach to semantic interoperability to enable sensors, devices, systems and services to express their contextual information and data by applying the ontologies to achieve semantic interoperability [see RE 2.4-3].

The work is based on ISO/IEC 30141, which is modelled as an ontology and focuses on the five facets of semantic interoperability of ISO 21823-1, namely transport, syntactic, semantic, behavioural and policy interoperability. The motivation for this standard is to be able to integrate the various existing IoT platforms and the different vertical domains (e.g. Smart Factory, Smart Cities, etc.) into an IoT reference architecture. The main contribution of this part of the semantic interoperability is a domain-based IoT reference model with an OWL specification of the IoT reference architecture. Furthermore, already existing ontologies are described.

The following are general findings from IEC PAS 63178 "Smart manufacturing service platform – Service-oriented integration requirements of the manufacturing resource/capability" developed by IEC/SC 65E:
→ The heterogeneity of cross-domain information models must be overcome.
→ Preference is given to multi-ontology and hybrid ontology approaches with a domain-specific top-level ontology and a corresponding underlying value.
→ The domain-based IoT reference model is accompanied by a formal machine-readable description.

IEC PAS 63178 focuses on the vertical integration and system operation phase with regard to semantic interoperability in industry. This standardization roadmap shows that several life cycle phases must be covered by semantic interoperability (see Chapter 2.3 and RE 2.4-2]. The IEC White Paper "Semantic Interoperability – Challenges in the digital transformation age" [80] gives an insight into requirements, challenges and potential fields of action for semantic interoperability.

Further international specifications for the interoperability of IoT systems are currently being developed. For example, the ETSI report TR 103 535 V0.2.2 (2019-03) SmartM2M [81] focuses on the guidelines for the use of semantic interoperability and describes its goal as follows: The main objective of this document is to promote semantic interoperability in the Internet of Things in order to raise awareness of its importance for industry and to unlock its potential economic value. A main focus is the development of guidelines for the use of semantic interoperability in industry.

The report describes the state of technology and refers to existing solutions from science, standardization and industry, with a focus on European projects and consortial projects. Only a few standards are mentioned. The authors conclude that the benefits of semantic interoperability are not yet being exploited in a way that will help mature the required technology. They describe mostly organizational and subjective reasons for this situation and give recommendations for overcoming the limitations. The analysis can be included as a contribution to the discussion in the relevant committees. However, the results of the ETSI TR are not sufficient.

To enable the development of cross-domain IoT services, standards such as oneM2M have been developed for use in commercial IoT platforms. An example of such a cross-domain IoT service is described in "ETSI TR 103 545 SmartM2M; Pilot test definition and Guidelines for testing cooperation between oneM2M and Ag equipment standards" as an example of cooperation between different standards such as AEF ISO 11783, ETSI EN 302 637-3 and oneM2M [see RE 2.4-1].

Information Data Lake

For technical systems, the concept of the Information Data Lake (IDL) currently represents the global structured container of all properties, data and information of different domains, which are communicated with standardized operations between producer (publisher) and consumer (subscriber). In between lies the enrichment of the raw published data with information (attributes of the information model) from the data processing processes and possibly also from AI approximation methods for the recognition of unknown data patterns (see Figure 20).

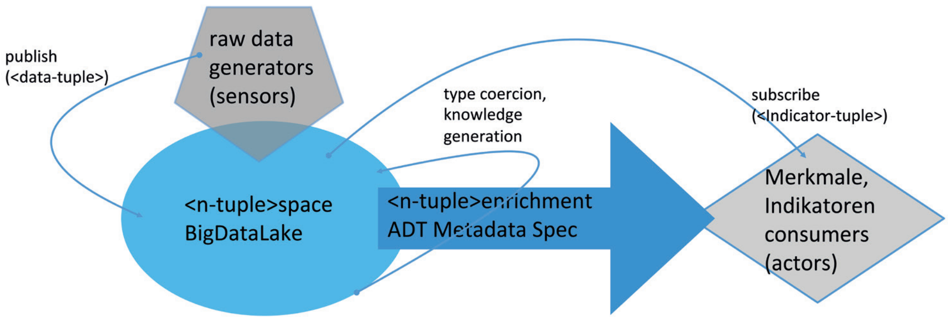


Figure 20: Semantic aspects of understanding when generating knowledge about things in the Big Da-ta Lake Concepts (Source: ETSI GS ISI 006 v1.1.1(82019-02) – ISI Enrichment Process (Data Lake)

Ontologies

Worldwide, there are numerous activities in the area of ontologies. Various committees (e.g. OMG, W3C, IDSA, or the Industrial Ontologies Foundry at NIST) address standard-oriented ontologies with varying degrees of coordination, which, from the perspective of the respective committee, should represent a domain-specific standard and thus a basis for interoperability. For such scenarios of distributed development of ontologies, mechanisms, processes and procedure models do exist. However, at the moment of the integration of several such supplied ontologies into a knowledge space, it cannot be formally secured on the basis of these artefacts whether all actors follow the same process, whether the same patterns are used for knowledge modelling, and whether result ontologies can be used and further developed according to the same process. If such different domains meet, which is an essential feature of Industrie 4.0, this leads to increased and avoidable integration and maintenance efforts.

If these domains continue to develop, changes become difficult to trace in the long term. This reveals a gap in the life cycle of ontology creation, usage and further development, since even with coordinated creation processes for one domain, the resulting efforts are difficult to recognize when combined with other domains [see RE 2.4-2].

Terminology

Numerous activities were initiated to define the new terms in the area of Industrie 4.0. For example, in the technical committee VDI/VDE-GMA 7.21 "Industrie 4.0", the "Terminology" working group is currently working on a uniform understanding of the basic terms, reference models and architectural concepts for Industrie 4.0. The aim is to develop the terms in coordination with the relevant working groups from national bodies, associations and industrial consortia in order to achieve a common understanding of the basic terms. The glossary was published bilingually (German/English) [78] and is publicly accessible via the Platform I 4.0 website [85].

The group is constantly active, expanding the scope of the glossary and consolidating entries with national and international bodies (e.g. IEC/TC 65/WG 23 *TF Terms and definitions* and IEC/TC 65/WG 1 *Terms and definitions*).

At international level, new terms related to IoT have been published in ISO/IEC 20924. The standard contains a number of terms that form a sound terminological basis for IoT. Furthermore, IEC/TC 65/WG 1 has submitted a proposal for the development of information technology terms.

Various duplications and contradictory terms are still circulating in the technical literature and in normative documents at national and international level, which, from the user's point of view, can significantly reduce the willingness to use them. For this reason it is also not clear how these terms can be assigned to the application areas in RAMI 4.0 [see RE 2.4-4].

2.4.3 Recommendations for action and application

2.4-1 Analysis of the results of ETSI TR 103 535 V0.2.2 (2019-03)

The analysis can be included as a contribution to the discussions in the relevant committees with a focus on "semantic interoperability":

→ Many semantically relevant information models already exist in industry, public or consortial standards that form a basis for semantic interoperability. These models are outside the scope of ETSI TR.

→ The term semantic interoperability in ETSI TR only reflects the information world. It appears that the report focuses only on the vertical flow of information to data-intensive applications. The industrial sector also includes the horizontal data flow and must also take account of real reactions (see Figure 18).

- → The ETSI TR seems to focus exclusively on uptime. The life cycle of products and plants, which ranges from planning to operation and maintenance, is only partially reflected.
- → The cooperation between IT ontology and OT information modelling is not yet established. However, this is urgently needed.

An example of such a cross-domain IoT service is described in "ETSI TR 103 545 SmartM2M; Pilot test definition and Guidelines for testing cooperation between oneM2M and Ag equipment standards" as an example of cooperation between different standards such as AEF ISO 11783, ETSI EN 302 637-3 and oneM2M. These activities must be observed and, where necessary, harmonized.

2.4-2 Cross-life cycle and robust designation of ontologies

It is recommended that a standard mechanism, vocabulary and methodology be developed for the cross-life cycle and robust designation of ontologies according to the elements and patterns used in them. On the basis of this, in a formal verification step, the quality of the matching of different ontologies when they are brought together in a knowledge space should be checked and recommendations for action for knowledge engineers should be derived. Relevant aspects in this context are, for example, the diversity of domains with their individual dynamics and processes for knowledge provision, as well as decentralized knowledge engineering and different ontology versions.

2.4-3 Conformity with the ISO/IEC 21823 series

DIN NA 043-01-41 IoT and other relevant bodies and committees should carefully review the current standards of the ISO/IEC 21823 series with regard to their direct reference to industry and report back to the mirror committee. Further DIN/DKE committees on semantics are to be included.

2.4-4 Duplications in terminologies

Duplications in terminologies, in particular with regard to their identical or synonymous application, should be identified, checked, differentiated and/or adapted in the competent bodies in order to avoid their erroneous application in further normative documents. It is recommended to consolidate the terms with current international standards, such as ISO/IEC 20924 and ongoing terminology activities in IEC/TC 65/WG 23 on vocabulary.

2.4-5 Recommendation of VDI/VDE 2193 Parts 1 and 2 for IEC standardization

The existing VDI/VDE 2193 (language of I 4.0-components) is available as of January 2020. Together with Part 1 which deals with the administration shell in detail, this forms an essential basis for interoperability between I 4.0-components. Therefore, this guideline should also be included in the canon of IEC standards on the administration shell. In existing concepts such as VDI/VDE 2193, socio-technical aspects must be taken into account in the interaction (e.g. human asset administration shell, human administration shells). It is recommended to elaborate this in a research project.

2.5 Integration

2.5.1 Status and progress since Version 3

Integration usually considers the ability of different systems and their components to connect as seamlessly as possible and to integrate into a larger whole, e.g. a common semantic basis. If we look at **Use Case 1** "Production marketplace" (see **Chapter 1.4.1**), it is absolutely essential that the systems and processes of all actors involved in word creation (buyers, marketplace operators, suppliers) can be seamlessly connected with each other.

For example, the buyer from Use Case 1 can forward the 3D printing request to the supplier and then automatically send a production order (e.g. in the form of CAD data) to 3D printers via a standardized interface. However, integration is not only responsible for effective and successful networking, but must always be seen in the context of interoperability (see **Chapter 2.4**) and communication (see **Chapter 2.6**).

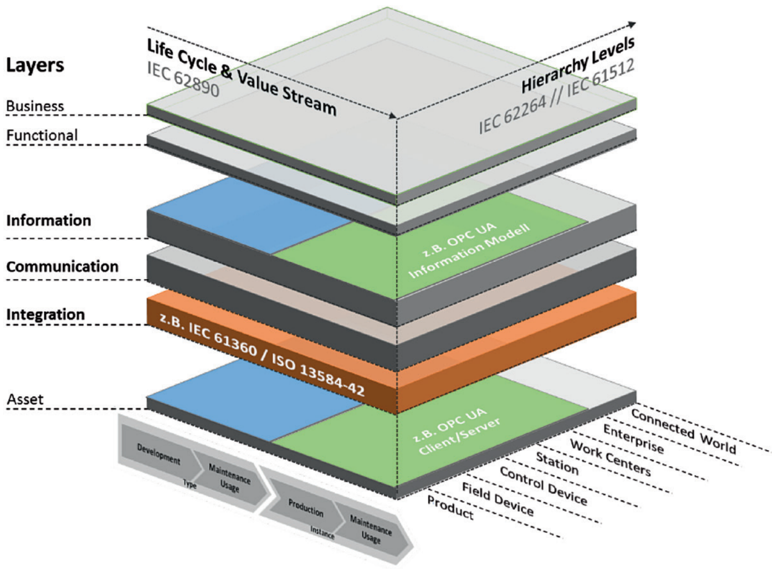


Figure 21: Integration layer in RAMI 4.0 (Source: Platform Industrie 4.0 [41])

The connections between the systems and processes involved are described in the information world by corresponding properties. The properties, which clearly describe the respective interfaces, are related to each other and correspondingly mapped in the administration shell, formally and in a machine-processable manner [57]. The role of engineering is becoming increasingly important at this point. Often the existing engineering solutions have to be adapted, extended and standardized for such seamless integration, as the following chapters show.

Engineering contributes to the development of normative integration concepts in which the important relationship information between the individual systems is to be provided as I 4.0-compliant information elements for further systems and their components. Integration standards are of great importance in this context, as they represent the bridge between the physical world and the information world.

In the information systems, numerous data are collected, processed and exchanged between the components during operation. In engineering, the combination of these individual components creates a new, higher level of functionality compared to that provided by the individual components of a plant alone [57]. The cooperation of the components and the data exchange is often based on heterogeneous interfaces, which have different data structures in the components to be connected at the time of the engineering process. This means that no component knows the data structures of the other component and must therefore always be adapted. This means that manufacturers and users are always confronted with high costs when replacing devices. Standardized integration procedures play an essential role here and can significantly minimize this integration effort.

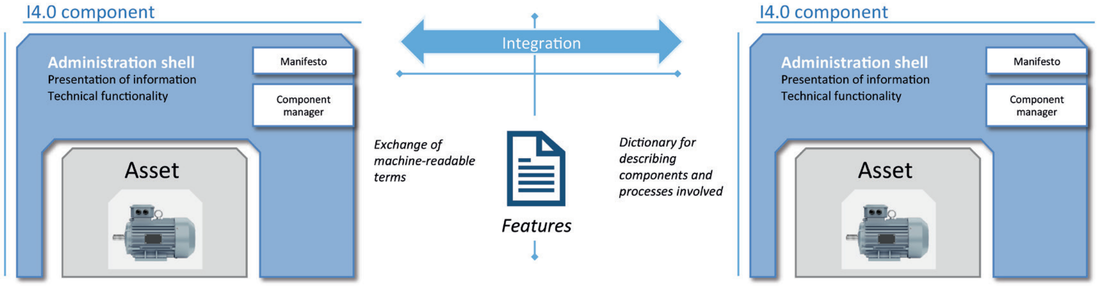


Figure 22: Exchange of properties between I 4.0-components

A technical system is usually characterized by the sum of the recognizable characteristics, i.e. properties. These are exchanged as machine-readable terms between the components involved in the communication (see **Figure 22**). Properties are therefore the main criterion for describing the relevant characteristics of an I 4.0-component. The comprehensive definition of the properties, e.g. in a dictionary to describe the components involved and their processes, helps both the manufacturer and the user to apply the system characteristics in a structured way in their environment. At the same time, due to the comprehensive and standardized semantics of the properties, the previously common "translation" from one data model to the other is no longer necessary at the interfaces. For such communication, however, a structure-independent abstraction is required, so that different but semantically identical structures are not obstacles in the communication process. This is not yet achieved by the current properties description.

If the processes are uniformly structured with RAMI 4.0 and the standardized formats of properties are used, mutually compatible process descriptions are created, which can also be related to each other in time using the RAMI 4.0 time axis. Since there is a demand for "automated engineering" in Industrie 4.0, such a solution is of fundamental importance. For example, in the future it will not be sufficient to place an order from the ERP system to a preconfigured MES. Rather, the MES requires additional information to identify the production line suitable for the product and other parameters such as the maximum price of the production, required delivery time, etc., so that the Production Manager of the MES can derive the necessary actions, which can lead to the rejection of the order.

In recent years, numerous standardization activities have taken place to describe different types of equipment and devices for industrial processes using structured lists of properties. For example, DIN's Working Committee NA128-00-01 AA "Properties Dictionary

Fundamentals and Rules" developed in the standards series DIN 4002 a procedure for the development and standardization of structural elements, compatible with the international document series ISO/IEC Guide-77, ISO 13584, IEC 61360-1, ISO 29002.

Other standards formed a basis for the structuring and feature description of product data technologies, such as the IEC 61987 series, on the description of process control devices, measurement and control equipment and their operating environments and operational requirements, and IEC 61360 Common Data Dictionary (IEC CDD) on a common repository of concepts for all electrotechnical fields, based on the methodology and information model of the IEC 61360 series. The CDD database, IEC reference collection of standard data element types and component classes is freely accessible via the IEC Webstore and is maintained by IEC Subcommittee 3D (IEC SC 3D). In addition, IEC 61360 provides a detailed introduction to the structure of the vocabulary and its use (IEC 61360-1), specifies the detailed data model (IEC 61360-2) and establishes important quality criteria for the content of the vocabulary (IEC 61360-6).

Furthermore, eCl@ss has established itself internationally as one of the most important ISO/IEC-compliant industrial standards (in accordance with IEC 61360/ISO13584-41) and is currently one of the most important reference data standards for the classification and unique description of products and services. The use of a central product master data server and the establishment of a uniform classification structure based on eCl@ss reduces the maintenance effort for material master data and data duplicates and creates more transparency of the data [43].

2.5.2 Current developments

The topic "integration" and the standardization of properties systems and further integration concepts for industrial IoT platforms and applications are dealt with in various international groups, e.g. IEC, ISO, eCl@ss und W3C. In Germany, the VDI/VDE, in particular its Society for measurement and automation technology, GMA, as well as the Automation section of the German Electrical and Electronic Manufacturers' Association (ZVEI) and the working group "Reference architectures, standards and standardization" of the Platform Industrie 4.0 deal with the questions of system integration and integration aspects through properties. These and other activities are described below.

eCl@ss and CDD
With over 40,000 product classes and more than 18,000 properties, eCl@ss covers a large part of traded goods and services in the respective industries. In spring 2017, the eCl@ss board of directors founded an expert group, the Digitalization Expert Group (DEG), to uncover the gaps in standardization and to deal with the topics around digitalization and Industrie 4.0. Among other things, DEG is responsible for coordinating all eCl@ss activities on digitalization, collecting requirements and managing cooperations with other bodies and associations [44].

IEC and eCl@ss have been cooperating since 2015 with the aim of achieving a sustainable harmonization of overlapping contents in IEC CDD and eCl@ss. Although standards for the descriptive properties of assets already exist in IEC and ISO, these are still far from being sufficiently developed [see **RE 2.5-1** and **RE 2.5-2**].

W3C Web of Things approach

The World Wide Web Consortium (W3C) develops open integration standards for IoT platforms and application domains. In particular, within the framework of the standardization work of the W3C, the following projects deal with numerous innovative topics that could be of preparatory importance for future web-based applications in Industrie 4.0 (see Chapter B.5). Based on this innovation model, W3C is currently working intensively on the *Web of Things* as an "enabler" of interoperability between IoT platforms and application domains [see RE 2.5-3]. The consortium is currently working on a formal model with a common representation for a *Web of Things (WoT) Thing Description*, which among other things describes the metadata and interfaces of an asset (here: *thing*). The appearance and behaviour of the *Web of Things* should be as completely identical as possible to the behaviour of the interaction models of people on the Internet (i.e. on the Web) and thus enable a transformation from a *Web of People* to a *Web of Things* [45].

The "Thing" architecture model according to WoT is classified by five essential elements: (1) behaviour, (2) forms of interaction, (3) data schemes, and (4) security configurations and (5) protocol connections [46]. Integration is seen as patterns, e.g. (integration) patterns (see implementation morphisms in the semiotic triangle, Figure 24), and is derived in different relationships, such as *thing-to-thing* or *cloud-to-gateway*. The provision of (meta-) data in the form of descriptions (WoT Thing Descriptions), especially for machines, and the ability to self-explain this data (inherence) is of central importance for the forms of interaction (Figure 23).

The concept shown in Figure 23 contains several interaction types, which allows the integration of different devices as well as different applications on the basis of a small vocabulary. For example, the WoT should define the application methods (process structures) for the formal description of interfaces. On the basis of this formal description, IoT end devices and services (possibly also microservices) can interact communicatively with each other without knowledge of or consideration for the underlying implementation, as well as across several network protocols. Furthermore, the WoT offers a standardized possibility to define the IoT behaviour and to derive a program generation from it. One of the challenges here is the development of standardized interfaces which, in contrast to the "classical" integration interfaces, are based on the connecting (as opposed to separating) character of elements in an (integration) pattern [see RE 2.5-3].

The WoT in W3C normatively references the following existing RFC's (Requests for comments) as a basis for implementation [47-61].

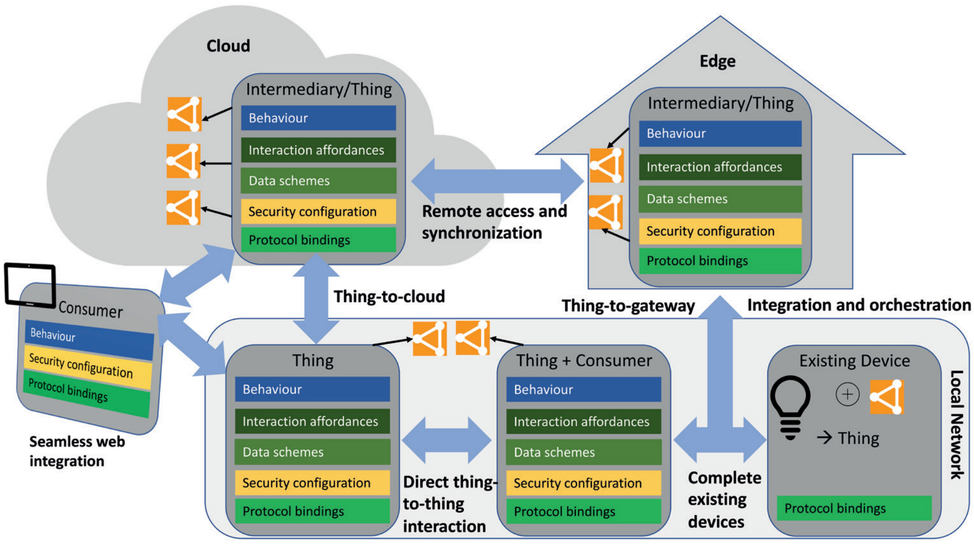


Figure 23: Overall picture of the interaction of things via semantic aspects of understanding „forms of interaction"

In view of the application in the world of work, which, from the point of view of Industrie 4.0, will be increasingly IIoT-based in the future, appropriate standardization appears to be absolutely essential. In particular, the development of normative guidelines for interoperability and the aspect of semantics, adapted to the natural behaviour of a human being on the Web are necessary. It is also necessary to consider a corresponding semantic concept, which is considered in the same way as for existing or currently developed standards.

When considering the individual implementation relationships, possible semantic relations – so-called morphisms – between the three relevant domains, the technology domain (for real or conceptual technical objects), the ontology domain (for the linguistic representation of properties or characteristics) and the semantics domain (for the representation and calculation of the meaning of a workpiece, in the form of mathematical calculi, here graph and algebraic data type theories), are created [62]. All three relations, graphically represented as a line between two domains, are illustrated in the semiotic triangle (see Figure 24) and can be understood as standardized "Implementation Guidelines". In other words, there will be standards that establish comparability for the three related "implementations".

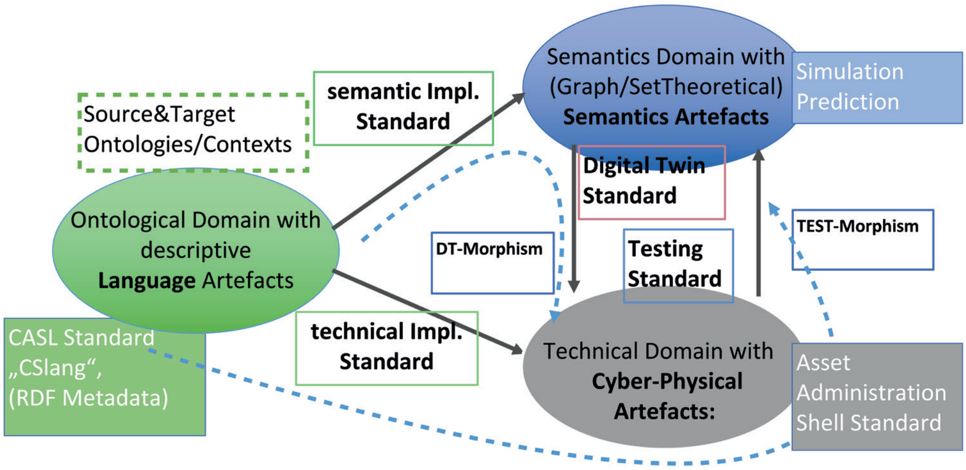


Figure 24: Semantic aspects of understanding the interaction between the three domains ontology – technology – semantics in the semiotic triangle (Source: DINCONNECT project specification (09-2018)).

Integration concepts on the basis of the IoT

Parallel to the basic topics such as uniform terminology, reference architectures and interoperability, ISO/IEC JTC 1 is currently carrying out intensive work in the field of system integration, such as ISO/IEC 30161 *Internet of Things (IoT) – Requirements of IoT data exchange platform for various IoT services*. The standard describes a data exchange platform for IoT, which consists of middleware components. The components are associated with network functionalities and include the network configurations, communication mechanisms and various functional properties of components for IoT.

Current international standardization activities (ISO/IEC JTC 1/WG 8, IEC/TC/65/WG 23) look at integration not only from a system perspective, but deal with integration in a complex context, with a view to full integration between the common reference architecture models. A good example is the creation of a metamodel in the Smart Manufacturing area (see **Chapter 2.2.2**). This is illustrated in **Annex B.5**.

National activities

At national level there are numerous activities on the topic of "integration". For example, DIN NA 043-01-41 AA**,** which in Germany reflects the work of JTC1/SC 41 "Internet of Things and related technologies", regularly contributes to current integration concepts based on the IoT reference architecture (ISO/IEC 30141) as well as harmonization activities with expert knowledge (refer to the NIA Annual Report 2019).

The **ZVEI working group System Aspects**, which is made up of participants from the member companies of the Automation Association and experts from research, has been devoting itself for several years to the topics and challenges from the perspective of manufacturers and users of automation technology products and systems. Already in 2010, the working group presented the definition of generally applicable models, terms, processes and strategies in the guideline "*Life Cycle Management for Products and Systems of Automation*", which represent a fundamental basis for a common understanding between operators and manufacturers on the subject of life cycle management. The results were later not only incorporated into international standardization (IEC 62890), but also found significant application in the reference architecture model Industrie 4.0 (RAMI 4.0).

In process control engineering (PCS), NAMUR has been working for years as a continuation of the project group PROLIST (Project Group "Lists of Characteristics") with the aim of specifying the characteristics and lists of characteristics from the PCS community in order to introduce them into international standardization and make them available to the public from the industrial sector [63]. Today the results are laid down in the eCl@ss database in the corresponding subject groups of the products. Furthermore, a large part of these characteristics is available in the IEC CDD.

2.5.3 Recommendations for action and application

2.5-1 Supplement existing standards (ISO 13585-1 or IEC 61360) on semantics
The data formats required in the information world are taken from ISO 13585-1 or IEC 61360**.** The properties of eCl@ss are also coded on this basis. However, administration shells or submodels require additional property types for operational use compared to the purely descriptive properties of an asset. These are states and parameters of the assets as well as their measured and actor values (dynamic data). Commands and entire functions (often called technical functions) must also be described using the same concepts. The concept of properties in today's standards is to extend such semantics in the data models to be able to represent dynamic values correctly. For example, this can be done with corresponding new attributes in the ISO 13584/IEC 61360 data model. Models for functions/commands are to be developed or existing ones defined in standards.

2.5-2 Sustainable and consistent harmonization of properties between eCl@ss and CDD:
Given the fundamental importance of standardized semantics for Industrie 4.0-components, a multiple coexistence of different standards for the same semantics is not acceptable, since it prevents the overlapping interaction between I 4.0-components. Parallel developments as in certain places today in IEC, ISO and eCl@ss must be coordinated:

The activities to harmonize the properties must be accelerated in the eCl@ss and IEC committees involved. In particular, the existing properties should be brought to the same semantic and syntactic level and adapted.

Standardized mechanisms and procedures for specifying new properties must be synchronised between eCl@ss and CDD to avoid further differences in properties. Ideally, the publishers of properties (and other structural elements, e.g. classes, values and units) have interlocked their standards after the harmonization steps to such an extent that semantically identical elements have the same name and code, i.e. mean the same thing. Common content should be kept identical in all databases or managed in a common database in order to structurally prevent the content from becoming divergent. The main publishers are IEC, eCl@ss and in future probably also ISO. The results should be made publicly available.

2.5-3 Standardization in the context of the Web of Things
WoT Integration concepts should be monitored in relevant national committees and analysed for their applicability in national standardization activities.

Due to the complexity of this topic in particular, attention should be paid to intensified cooperation through liaisons between standards setters, but also through Category C liaisons between standards setters and open source and industry consortia.

In contrast to the existing "classic" protocol standardization, which is mostly gateway-based and may not be able to meet the requirements of modern direct communication, a seamless integration of I 4.0-components across all layers with full semantic support (see **Annex A**) is to be developed. As a proposal, this class of standards should be initiated or structured according to the IoT reference architecture (ISO/IEC JTC1/SC41/30141).

2.6 Communication

2.6.1 Status and progress since Version 3

An essential aspect of the implementation of Industrie 4.0 is the networking of all instances involved in value creation. This concerns, for example, the implementation of product marketplaces (**Use Case 1**, see **Chapter 1.4.1**) or assistance systems (**Use Case 2**, see **Chapter 1.4.1**).

When realizing product marketplaces, the first priority is global communication between service user, marketplace and service provider. However, an integrated data concept also requires seamless communication right into the production area.

Future assistance systems will additionally require broadband communication, e.g. for augmented reality applications, and deterministic communication for the greatest possible synchronicity between the production process and assistance functions.

The communication systems used today will be supplemented or replaced by new developments. Examples include Time Sensitive Networking (TSN) or developments in connection with 5th Generation mobile networking (5G).

IEEE or 3GPP communication standards specify the physical layer and the medium access control sub-layer for user data traffic. If no higher layers of the Internet such as IP, TCP or HTTP should or can be used for industrial communication systems, corresponding standards for services, protocols and profiles are available in the IEC 61158-1 and IEC 61784-2 standards series. Industrial radio communication systems are standardized in IEC 62591:2016 (WirelessHART), IEC 62601 (WIA-PA), IEC 62734 (ISA100a) and IEC 62948 (WIA-FA). In addition, the series of standards on coexistence management for radio communication solutions IEC 62657-2 is to be mentioned.

The requirements for communication in Industrie 4.0 will be very diverse. Consequently, very different wired and wireless communication systems will be used. With OPC UA, an interface standard has been established that bridges the heterogeneity of industrial communication systems on both the communication and the information level. This interface standard supplements the existing communication solutions. It is based on concepts such as a service-oriented architecture (SOA) and information models (OPC UA Companion

Specification) to describe devices and their capabilities. An SOA makes it possible for components, machinery and plants to act more flexibly if they are not configured and programmed to carry out a specific production task, and are able to offer their basic capabilities in the form of services. These include the ability not only to transport data from devices (measurement values, settings and parameter values), but also to describe them semantically in machine-readable form.

Initial situation for wired communication

Industrial communication systems already offer sophisticated solutions for high requirements for wired communication based on IEEE 802.3 (Ethernet). For Industrie 4.0-networks, which include not only the shop floor but also the office floor, there are additional requirements in addition to the previous requirements regarding modularization, the flexible addition, removal and rearrangement of modules. In addition to the non-hierarchical networking of components, the increasing number of sensors and actuators, as well as extended network connections of operating equipment for e.g. diagnostic purposes, not only result in increasing data traffic, but also in changed requirements regarding the topology of the networks.

In terms of topology there are two worlds today. One is the active, linear topology commonly used in industrial automation, in which there is a switch in each subscriber that establishes both the incoming and outgoing line as well as the internal connection to the device. In contrast, in structured building cabling we have a star-shaped cabling with the three hierarchical levels campus, building and floor.

Initial situation for radio-based communication

Communication resources for radio-based communication cannot be expanded to the same extent as would be necessary to meet rapidly growing communication requirements. In particular, the radio spectrum is very limited. Today, radio communication uses radio spectra that are usually not exclusively available for a single application. Currently, radio applications are only prioritized through the allocation of frequencies by the regulatory authorities. The flexibility of the production processes and the mobility of the instances also make it possible, however, to adapt the communication relations to the degree required. IEC 62657-2, for example, describes a frequency-independent coexistence management that can be implemented manually or automatically. Management and control services are provided by flexible communication systems (such as mobile radio systems) in order to adapt the communication system during operation to the respective communication requirements.

With the **5G Alliance for Connected Industries and Automation (**5G-ACIA**)**, an international expert committee has been established in Germany in which mobile phone equipment manufacturers, mobile phone operators, automation specialists and users of industrial radio-based communication exchange information and ideas and prepare standardization projects for the 5th mobile phone generation [see RE 2.6-A1].

The current developments and implementations for industrial network communication, which were addressed in the Roadmap version of two years ago, are as follows:

Heterogeneous industrial networks
For industrial communication, technologies such as TSN, 5G, new WLAN developments and OPC-UA are currently being discussed. Concepts for integrating industrial Ethernet solutions in 5G are discussed in a white paper of the 5G-ACIA [64]. It should be noted that the currently available mobile radio solutions can transmit IP traffic, but not Ethernet packets. The aim of the work is vertical integration. Therefore 5G-ACIA also has the integration of TSN and OPC UA on the agenda. Such activities are not known for future WLAN solutions. A connection with TSN is assumed. The implementability of seamless transitions through standardization is still unclear. [RE 2.6-1] is derived from this.

Network management
Industrial communication is characterized by extremely diverse networks, each with its own device and network management solutions. The current state of knowledge is not sufficient to initiate a standardization of management services for 5G, Ethernet, Internet, TSN, WLAN etc. for industrial communication. First of all, it should be clarified which types of equipment and which parameters should be taken into account for interoperable management. For 5G networks in particular, it is not clear to what extent standardization is possible in this respect. [RE 2.6-2] is derived from this.

Parts 1 [65] and 2 [66] of IEC 62657 are available for the coexistence management of industrial wireless solutions. Parts 3 and 4 of the standards series are in preparation.

Integration in Industrie 4.0
The requirements for the uniform handling of communication systems of the most diverse technologies in the life cycle of production plants also affect the role of these communication systems. They are not only means to a (communication) end, but also part of the production plant. In contrast to office communication, the automation application places changing demands on industrial communication due to the increasingly flexible production process.
Communication assets should therefore also be developed for Industrie 4.0-components. In that regard, it is necessary to examine which assets would best benefit from the definition of a digital representation. It is under discussion whether, in addition to active assets such as modems, switches, base stations, etc., passive assets such as lines, connectors or antenna systems should also be described with administration shells. The current state of knowledge is not sufficient for standardization, which is why [RE 2.6-3] is formulated.

Data traffic models
In mobile communications, data traffic models are used to design the networks. This is not yet common practice in industrial communication. With Industrie 4.0, video transmissions, augmented reality applications and tactile controls will be increasingly used. Therefore, the specification of data traffic models will also be necessary for industrial communication. Based on this, the necessary settings for different data traffic classes can be made for TSN, 5G network slices, Ethernet and WLAN, for example. First concepts are presented in a 5G-ACIA White Paper [67]. [RE 2.6-4] proposes the continuation of this work in preparation for standardization.

Reliability assessment
The growing orientation towards mass-market communication technologies and the growing complexity of communication networks as a result of Industrie 4.0 is giving rise

to a more pronounced separation between the providers and users of communications services. This also results in the need to formulate, determine and review requirements for the provision of communications services in a clear and invoiceable manner, especially in cases where the provision of communications services is subject to charges.

VDI/VDE Guideline 2192 [68] specifies characteristics and influencing variables of interactive technical systems for use in the standardization of Industrie 4.0-systems. The focus is on the non-functional properties that allow quantitative statements about the service performance of the systems. These statements are mapped to parameters known as quality of service (QoS) [68]. [seeRE 2.6-5].

Evaluation of real-time communication

Real time is an essential characteristic of cyber-physical systems (CPS). As it is predicted there will be discussions on the topic of real time in long-distance, flexible, adaptive and autonomous network systems, work on a standard that gathers together and unifies the concepts and properties relevant to industrial real-time systems should be given urgent priority. Part 4 of the VDI/VDE Guideline 2185 [69] on industrial radio communication systems provides a first approach. [see RE 2.6-6].

Validation and testing

The stringent requirements of industrial communication with regard to the functionality and reliability of the devices and systems mean that a clear testing strategy is required. In that regard, account must be taken of the fact that functionalities that are not obligatory can result in incompatibilities. It is also necessary to remember that different stack architectures are possible, the components of which are specified by different standards setters (e.g. 3GPP, IEEE, ETSI, IETF, IEC). Provisions must be put in place stating how the compliance and interoperability of the communication implementations are to be verified. A conformity assessment strategy is advisable because of the many potential manufacturers of industrial communication devices.
There is a 5G-ACIA white paper [70] discussing aspects of testing 5G components The conclusions are also applicable to other communication technologies. In addition, the knowledge base for standardization is not yet sufficient. [see RE 2.6-7].

Security

In the working group AG3 of the Platform Industrie 4.0, the topic of information security (IT security) is also discussed as regards communication. Additional requirements result, for example, from the flexibility of the applications and thus the necessary agility of communication and the characteristics of the communication technologies (e.g. necessity of cell change, adaptivity of the connections). Current developments, recommendations for action and application for security are discussed in Chapter 3.2.

Frequency spectra

Efforts to obtain a worldwide allocation of frequency spectra for industrial automation applications have been actively assisted by experts in measurement and automation technology. The 5G-ACIA prepared a Technical Report to support the harmonization of the radio spectrum for industrial automation at the World Radio Conference 2019 (WRC-19). 14 new use cases of industrial automation were described. The submission of the results of this work to the ITU-R (WP5A, WP5D) and RSPG (Advisory Body to the EU Commission) was prepared. This was done in close cooperation with the relevant government agencies and administrations.

With the administrative regulation for frequency allocations for local frequency use in the 3,700-3,800 MHz frequency range (VV Local Broadband) [71], "Bundesnetzagentur" (the German Federal Network Agency) makes this range available for local applications. As a result, these frequencies can be used for industrial automation or I 4.0 in particular, according to the notified requirements [see RE 2.6-8].

Local mobile networks for industry
In the 5G-ACIA, discussions on the use of 5G technologies for non-public networks have begun [72]. Decoupling industrial 5G networks from the public mobile network increases the acceptance of 5G as a building block for Industrie 4.0. The feasibility of implementation via standardization is, however, still unclear. [see RE 2.6-10].

Industrial wide area networks
Network slicing concepts should enable non-public, industrial 5G subnets to be virtualized in public 5G networks. The concept envisages that several logical networks with customized quality guarantees can use the same physical infrastructure. This should enable the different communication requirements of industrial automation to be served.

The essential requirements for network slicing and the corresponding technical specification to enable network slicing in the 5G architecture were developed by 3GPP SA1 and SA2. To use network slicing, it is necessary to specify how the specific requirements of the application can be taken into account [see RE 2.6-10]. It is not yet clear whether standardization is needed beyond the work of 3GPP.

Industrial location management
The localization of objects is currently one of the most urgent requirements of industrial automation. A large number of solutions of different resolutions and accuracies are known. The point of exchange of position data and related information is open. The requirements for the transmission of position data and the service and parameter specifications that exist are to be compiled. The state of the art is to be evaluated and suitable specifications selected or further developed. Despite the need for localization, there is currently little industry interest in standardization. This creates the danger of many individual and proprietary solutions that cannot be used uniformly in automation systems [see RE 2.6-11].

2.6.2 Current developments

The current and future developments in industrial communication can be characterized as follows:

→ The amount of communication within and between the hierarchy levels of the factory will increase considerably. Communication between spatially and organizationally distributed instances will have to be wireless, often for reasons of flexibility or because of the mobility of the instances themselves.
→ Communication requirements do not permanently exist in the same way over the entire life cycle of a production plant, but change according to the flexibility of production. The

volatility of Industrie 4.0-processes also requires communication between application processes and communication processes.

Heterogeneous industrial networks

5G-ACIA has initiated two work items on this topic. In the first work item "Integration of 5G with Time-Sensitive Networking for Industrial Automation" concepts for the integration of TSN according to the project IEEE/IEC 60804 [73] (IEC 61672-1, IEC 61672-2) are developed. The second work item "Integration of OPC UA with 5G network" will discuss the possibilities of integrating 5G and OPC UA [see RE 2.6-1].

Network management

In the work item "5G Network Exposure Interface for Enterprises" of the 5G-ACIA, measures are discussed to enable uniform access to the network resources of non-public networks or dedicated network services of mobile operators. Access to the network via a well-specified and easy-to-use interface should support the management of device connections, configuration and the management of communication services. Management functions such as network start-up or connection establishment (plug and work) must be harmonized. For example, in DIN SPEC 16593-2 "Mechanisms for bootstrap, announcement and location of industrial IoT components", which is currently under development, a uniform mechanism for the dynamic mediation of communication partners in Industrial IoT will be defined. This enables communication partners to find each other in an Industrie 4.0-system – independent of a specific implementation technology of the IIoT component.

The consideration of the following mechanisms for mediating the communication partners is planned:

→ Communication infrastructure for the start phase of an IIoT component (bootstrap) with integral consideration of the security aspects for this phase
→ Making the communication endpoints known so that they can be looked up (advertisement)
→ Looking up communication endpoints (lookup).

In the course of the activities, this DIN SPEC, a detailed specification of the technological implementation, which is complete for an implementation, will be defined in addition to the conceptual specification of a uniform mechanism for a dynamic mediation of IIoT components so that the specification can be used by developers for the implementation of the mechanism. The DIN SPEC Workshop is to be offered and used as an opportunity to compare the contents of all solutions currently under development in parallel and use this as a starting point for the specification. It is also intended to combine the expertise of different specialist areas (IT, security and cloud, mechanical and plant engineering, etc.), whereby a defined solution for the question posed here can be consolidated (on an interdisciplinary basis). This DIN SPEC is also intended to be integrated into the existing standards landscape and recommendations of relevant bodies, such as the Platform Industrie 4.0.
Within the framework of the DIN SPEC, in particular

→ possible communication partners are identified and requirements for the mediation of these communication partners on the basis of possible application scenarios are derived,
→ concrete existing solutions for the (dynamic) mediation of communication partners are compared and evaluated,

→ in an integral consideration of security mechanisms of these solutions, the requirements for a solution pattern for the implementation are defined,
→ the description of a solution pattern is derived, and
→ the concrete implementation is described.

[RE 2.6-2] is derived from this. The "VV Local Broadband" (administrative regulation) provides for agreements between neighbouring users for local frequency uses in the 3,700–3,800 MHz frequency range. Here it will be examined as to whether IEC 62657-2 can support this process.

Reliability assessment
The work item "Key Performance Indicator (KPI) for 5G technology-enabled connected industries" of the 5G-ACIA also addresses reliability assessment. Together with the VDI/VDE Guideline 2192, these could form the basis for a standardized reliability assessment of industrial communication solutions [see RE 2.6-5].

Evaluation of real-time communication
In the work items "Performance testing – Field trial – Objectives, Requirements and Methodology" and "5G Performance Evaluation for Connected Industries and Automation" of the 5G-ACIA, methods for evaluating the real-time behaviour of industrial 5G solutions are discussed. The approaches and conclusions should be evaluated from the perspective of heterogeneous industrial networks and adapted if necessary [see RE 2.6-6].

Frequency spectra
Discussions on the further development of spectrum regulation (i.e. the conditions of current and future spectrum allocation) as well as discussions on the impact on industry will continue in 5G-ACIA. Another topic is resource utilization options to enable 5G Industrie 4.0-solutions, including network slicing. Various models for spectrum provision for Industrie 4.0 are being discussed in Europe and globally [see RE 2.6-8].

The applicability of existing standards or standards under development must be examined. If necessary, profiles must be specified to enable a conformity test to be carried out in order to ascertain the interoperability of products from different manufacturers.

Here it should be examined what an ideal network structure for Industrie 4.0 looks like, including wireless communication. This includes communication within Industrie 4.0-components as well as networking between the various, partly mobile, Industrie 4.0-components, communication with higher-level automation devices and connection to commercial IT, and the cloud for data storage and cloud-based services. The solutions found are to be standardized. In order to implement diagnostic and monitoring functions in an Industrie 4.0-network, the infrastructure components of wired communication systems, both active (routers, switches, repeaters, etc.) and passive (lines and connectors), require a virtual representation. The properties (product descriptive and operational data) and the status information of the infrastructure components are to be standardized in order to provide a uniform viewpoint.

In order to make use of these services within the application process, it would make sense to regard communications devices as Industrie 4.0-components, and to take account of the aspects laid down in the layer of RAMI 4.0 during their development. New communication technologies and the described adaptivity of communication systems also place new demands on security. Furthermore, because of the mobility and determinism of applications, communication systems must provide positioning and time synchronization services.

2.6.3 Recommendations for action and application

2.6-1 New standards for global mobile network technologies should be configured or existing standards expanded in such a way as to enable a seamless transition between local industrial networks and industrial mobile radio networks. Starting points for the standardization of such heterogeneous, industrial networks can be the documents of the 5G-ACIA for the integration of Ethernet, TSN and OPC-UA in 5G.

2.6-2 Services and interfaces for the management of the various industrial communication networks should be specified uniformly and from an application perspective. Account must be taken of the need to distinguish between the provision of networks (management services) and the provision of communications services (control services).

2.6-3 Communication devices with adaptive functions for device and network management are to be modelled as Industrie 4.0-components. Appropriate properties and services are to be specified for a communication sub-model of an administration shell.

2.6-4 For the planning of communication networks (wired and wireless) a model has to be developed with which industrial data communication scenarios can be specified.

2.6-5 Standards for the reliability assessment of communication networks and communication services are to be developed, which allow a quantitative, transparent and contractually secure assessment from the perspective of industrial applications at the interface between provider and user.

2.6-6 Parameters and methods for the evaluation of industrial real-time communication systems (wired and wireless) are to be summarized and uniformly defined in a standard.

2.6-7 Communication standards for Industrie 4.0 are to provide test specifications that can be used to demonstrate the performance, conformity and interoperability of products.

2.6-8 Efforts to obtain a worldwide harmonization of frequency spectra for industrial automation applications should be actively assisted by experts in measurement and automation technology. Industry associations and Platform Industrie 4.0 should formulate arguments and requirements for administrations (e.g. BNetzA in Germany) for consideration in frequency use planning. These should be internationally coordinated. The regulation applicable to Germany for frequency allocations for local frequency use in the 3,700–3,800 MHz frequency range should apply worldwide in the interests of international harmonization. It is also recommended to harmonize the concepts for non-public industrial network operation and for cooperative network operation with a public network operator.

2.6-9 New standards for global mobile network technologies should be configured or existing standards expanded in such a way that they can be used to provide a non-public local industrial network. The starting point should be the 5G-ACIA White Paper "Non-public Networks" [72].

2.6-10 Using the network slicing concept, it is possible to virtualize non-public industrial 5G subnets in public 5G networks to serve applications and services with Industrie 4.0-specific communication requirements. However, to enable the seamless integration of (heterogeneous) industrial networks with 5G networks, open interfaces between the two types of infrastructure still need to be defined. Attention needs to be paid to the ability to position assets with 5G infrastructure.

2.6-11 Industrial location management requires uniform standardization of the following aspects:
(1) technologies for determining location data;
(2) formats for location data;
(3) agreements on data storage (central/decentralized);
(4) protocols for data transport;
(5) applications and visualization tools.

2.6-A1 With reference to the rapidly progressing specification process for mobile radio systems in 3GPP, publications on many aspects of communication are emerging in 5G-ACIA. These publications can also help to reassess industrial communication from the point of view of its use for Industrie 4.0. Topics such as the integration of TSN and OPC UA in 5G, data traffic modelling or the assessment of the reliability of communication networks and communication services can be a source of information for future standardization projects. It is therefore recommended to pay attention to the work of 5G-ACIA.

2.7 Humans and work

2.7.1 Status and progress since Version 3

In work processes in Industrie 4.0, humans are involved with various tasks as actors in the socio-technical work system, e.g. as operators of machines, maintenance staff, production planners or programmers. The criteria of user-friendly, sustainably successful work can be taken into account in the planning of new and redesigned work systems with foresight. When humans with their abilities, skills, performance and limits are included in the design, ergonomic, efficient and flexible work systems are created.

The hierarchy of criteria for people-friendly work (see Figure 25) guides standardization work in the field of ergonomics. The fundamental criterion is the feasibility of activities within the context of the physical and mental performance capacity of human individuals. In addition, work must be harmless; accidents and damage to health, but also mishandling, must therefore be avoided by appropriate design. Nowadays and in the future, numerous assistance systems and automation solutions in ergonomic design are taking over or provide support in tasks that would otherwise be impossible to perform or that would be harmful to health if performed by a human. Adaptive and adaptable technologies enable this support to be tailored to the individual involved. Work must not have any impact on the individual and should therefore be designed for an optimum workload, thereby keeping the person from being physically or mentally overworked or underworked.

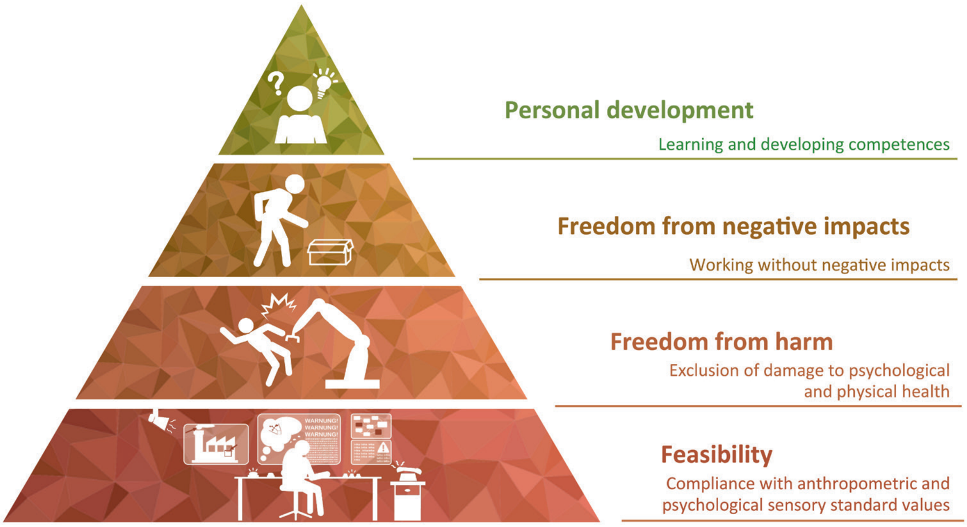


Figure 25: The criteria for people-friendly work, according to Hacker (2005)

The developments within Industrie 4.0, such as dynamic cyber-physical systems, high information availability and complex human-technology interaction can have a load-reducing effect. If inappropriately designed, however, they can have the opposite effect, e.g. monotony can arise when a person tends to become an assistant of technology and primarily carries out monotonous, undemanding residual activities. As far as an individual's workload is concerned, the two extremes – overwork and underwork – must be avoided. The highest criterion is that it is a case of designing work in such a way that it promotes the development of the individual by enabling them to learn and develop new skills. By continuous and individualized qualification of employees, by transferring responsibility for a part of the work system and an ergonomic design of the human-technology interaction, dequalification can be avoided and learning can be promoted.

Principles of ergonomics for the design of work systems

DIN EN ISO 6385, the current edition of which is 2016, is the internationally accepted basic standard for work systems. It forms the basis for the ergonomic design of the interaction of workers and work equipment with human-technology interfaces in a work organization for processing work tasks and activities in a work area or at the workplace and a work environment (see **Figure 26**). The contents of the standard apply to a wide variety of work systems, such as those used in production, in the provision of services or in knowledge-based work or logistics. Fundamental concepts of human-centred design of a work system and suitability for use of given work equipment are anchored in the standard. In addition, central terms for ergonomic work design are defined and the essential components of a work system that must be designed are also named.

Design of ...

Figure 26: Elements of a work system that can be designed in accordance with DIN EN ISO 6385

The present chapter is structured on the lines of these elements. Not only the individual design elements of the work systems, are important, however. In times of interconnected, dynamic and complex production systems, the interactions between the elements also play a special role. Since humans in Industrie 4.0 work systems often interact with technical equipment (e.g. machines, workbench), legal requirements become relevant here, which relate on the one hand to their manufacture (e.g. Machinery Directive 2006/42/EC, 2009/127/EC) and on the other hand to their use in everyday operations (e.g. workplace regulations).

In countries of the European Union, this division plays a special role, as the underlying regulations can also refer to so-called harmonized standards for further information, which can then give rise to a presumption of conformity for successful implementation. Safety and ergonomic requirements are described in the Machinery Directive and specified by means of references to standards. If the ergonomic design of work tasks is demonstrably based on the DIN EN 614 series, and that of interaction and information interfaces on the DIN EN 894 series, essential requirements for the design of work tasks and activities on machines are thus implemented. Of course, other requirements or non-harmonized standards (e.g. the DIN EN ISO 9241 series) can also be used for design purposes, provided that proof of comparability is also provided if required. When designing the safety of machinery, it is therefore recommended to be guided by the ergonomic requirements of standards that implement the Machinery Directive.

Exemplary Use Case "Vehicle assembly assistance system"

As already briefly described in Use Case 3 (see Chapter 1.4.1) digitalization offers comprehensive technical possibilities to support different types of work with assistance systems. The following notional use case is by way of example, and incorporates aspects of these functions. The job at hand is the final assembly of the interior of a car by an assembly technician as part of automobile production.

The technology used is an exoskeleton as dynamic seat support, a handling-supporting, collaborative robot for the handling and installation of large parts of the vehicle interior, and data glasses that can be used, depending on the situation. These provide assembly and quality assurance information relating to variants, whilst at the same time making use of camera technology to document the process and, in specific situations, to make recordings (including verbal recordings) of suggestions for improvement or of similar information provided by assembly personnel. Communication possibilities with superiors, specialists etc. are also included.

The actors here are: assembly personnel, assembly managers, work system planners, work process planners, assembly control, mechanical and electrical maintenance personnel, maintenance personnel for the software and hardware for the assistance systems and functions. To avoid the production line coming to a standstill following the failure of a technical aid, it must still be possible for the assembly process to be carried out without robotic or assistance systems. Likewise, limit values should not be exceeded or gone below. The result of the process is the assembly of an interior component (e.g. seat bench, dashboard).

Vehicle and interior component are available on the conveyor belt and are guided power-assisted into the vehicle by one person with an exoskeleton chair and handling robot. Rough and fine positioning of the component is carried out using human-robot collaboration. Optionally, variant-specific information for the screw connections can be queried by means of data glasses, which can also be used to record suggestions for improvement via images or language can be used. The documentation of the work step is also done via the camera system of the data glasses.

Design of the work system

Industrie 4.0 can open up new potentials of flexibility for companies in the design of work and value creation processes. An ergonomic design of work systems supports the planning, implementation and operation of Industrie 4.0-solutions through a systematic and strategic approach.

Design of work organization

The organization of work can be subdivided into the operational and the organizational structure. The design of the operational structure involves processes within the company being organized in such a way as to ensure that products are manufactured or services are provided. Organizational structures must be designed to enable and support the operational structure. [see RE 2.7-2].

Design of tasks and activities

An ergonomic design of changing as well as new tasks and activities also offers the chance to maintain and improve the performance, health, safety and well-being of workers in the future. The following examples can be given as principles for the permanent optimization of the workload:

- → Avoiding overworking, underworking, unnecessary repetition, otherwise unbalanced workloads, physical disorders or feelings of monotony, psychological saturation, boredom, dissatisfaction.
- → Giving working employees meaningful feedback on their task processing.
- → Avoiding working in isolation without opportunities for social and professional contact.
- → Giving workers an appropriate degree of freedom of choice in terms of priority of tasks, pace and approach.

Design of products, equipment and interfaces

According to DIN EN ISO 6385, work equipment includes tools, hardware and software, machines and other components used in a work system. Interaction with employees takes place via interfaces, the design of which should be oriented to the properties and characteristics of humans. For the objective of safe and healthy work design, the guiding principle of ergonomic work system design appears to be more comprehensive and far-reaching than that of designing work equipment suitable for use.

In DIN EN ISO 10075-2 "Ergonomic principles related to mental workload" (currently under revision), for example, it is recommended to allow for changes in the mode of signal representation in order to avoid monotony and to allow for individual execution of tasks. Opportunities and risks associated with Industrie 4.0-technologies in this respect are discussed in the current revision of the standard.

Smart devices, wearables and similar technologies networked with services lead to a blurring of the boundaries between product, system and services. As a result, new interactions between humans and machines or technical systems can arise, which pose a challenge for the assessment of possible hazards and ergonomic design. Topics such as "bring-your-own-device" or "user experience", which occupy an increased space in the discussion and also in standardization (see definition of "user experience" in ISO 9241-210), show that a successful and economic application of systems depends to a large extent on the experienced quality of the use of these systems.

Design of work environments, work spaces and work stations

DIN EN ISO 6385-12 contains definitions of terms as well as requirements for a human-friendly design of the working environment, working space and work station, taking into account the interaction with other elements of the work system (such as work equipment). The working environment therefore includes physical, chemical, biological, organizational, social and cultural factors surrounding a worker. The standard requires, among other things, that objective and subjective assessments of the environment be taken into account, that recognized limits for the maintenance of health, safety and well-being be observed and that it be possible for workers to influence the environment.

The work space is the area assigned to one or more people within the work system in which they carry out their tasks. The work station describes the combination and spatial organization of the equipment within the work environment, under the conditions required by the tasks. The standard specifies, among other things, the following requirements for the design of the work space and work station:

→ Working with both static posture and the ability to move around shall be possible.
→ A safe and secure surface shall be provided, from which bodily strength can be applied.
→ Body size, posture, muscular strength and body movements shall be considered.

Specific aspects of the work environment are covered in existing standards (e.g. lighting in the work place in DIN EN 12464-1). Furthermore, there are also some VDI guidelines on the topic (e.g. VDI 2058 Part 3 "Assessment of noise in the working area with regard to specific operations"). The essential requirements are covered in the *Technische Regeln für Arbeitsstätten* (*ASR*) (Technical Rules for Workplaces). These give detail to the requirements of the *Arbeitsstättenverordnung* (German Workplace Ordinance).

Design of work so that it promotes learning and the development of competencies

Work tasks which are not only designed to be executable, harmless and free of impairment, but also offer opportunities for personal development, fulfil the essential criteria of human-friendly work design (Figure 22) and are considered to be beneficial to health and learning – and consequently motivating and productive [87–90].

In standards, the promotion of learning is mostly mentioned in the context of ergonomic design. Engaging with the requirements of a work-related task and the mental stress and mental strain associated with this can initiate a learning process. In this way, learning can be facilitated (DIN EN ISO 10075-1). In addition, existing standards provide information relating to the design of software in such a way that it encourages dialogue between humans and the technical system in a manner that promotes learning (DIN EN 29241-ff/ ISO 9241-ff).

Taking the use case "Assistance system" outlined in Chapter 1.4.1, this means that performing the assembly task and the associated mental interaction with the task constitute a learning process. In this way, the person is able to learn how to perform the task, will be able to continually improve their command of the movements required, and will be able to increase their understanding of the system and how the various components are interrelated. Likewise, they will gain more knowledge of the reasons why errors and faults occur and an understanding of the system.

2.7.2 Current developments

Design of the work system

Various recent studies confirm that Industrie 4.0 can only be successful and sustainable in a work system once it has achieved a certain level of maturity: According to the study into the development of skills in the context of Industrie 4.0 that was carried out by acatech [67], the most important skills required by companies are as follows: data evaluation and analysis (60,6 % of companies), followed by process management (53,7 %). These appeared ahead of IT-specific skills in the list. The outcome of the study entitled "*Industrie 4.0 im Mittelstand*" (Industrie 4.0 in small and medium-sized enterprises) carried out by Deloitte in relation to specific Industrie 4.0-projects in small and medium-sized enterprises during the past 12 months was that 86 % of those questioned were in the course of optimizing their processes. Against this particular backdrop, the design of the work system must always be carried out in parallel to the technical planning of an Industrie 4.0-solution.

DIN EN ISO 6385-12 defines the design of work systems as an iterative and structured process that comprises a number of design phases and leads to redesign or restructuring. In addition to DIN EN ISO 6385-12, a variety of other standards contain information of relevance to the process of designing a work system: For example, DIN EN ISO 27500:2017-07, DIN ISO 45001:2018-06 or DIN EN ISO 9000 ff. describe framework conditions for work system design, while DIN EN 16710-2:2016-10, for example, presents analysis methods for work system design. Due to the complexity of the topic, none of the standards include any specific information on operational implementation; as a consequence these must be determined on the basis of the situation that applies within each company.

Important impulses were generated in March 2019 by the international ISO standards workshop "Ergonomics standards for robotic, intelligent and autonomous systems". The results of the working groups on robotic, intelligent, autonomous systems will be incorporated into ISO/TR 9241-810, which is to be revised. This group will also evaluate the various activities in the field of ergonomics, smart manufacturing and exoskeletons. At national level, within the DIN Standards Committee Ergonomics, the Working Group "Work and product design in Industrie 4.0" is responsible for determining in detail the need for amendment of ergonomics standards [see RE 2.7-1 and RE 2.7-2].

When considering the role of human beings in Industrie 4.0 value-added systems, a socio-technical perspective is of great benefit for forward-looking work design. A key issue for the socio-technical process of work system design is the approach to worker participation. Often the application context of I 4.0-components is still unknown, so that participation of the workers does not seem feasible. At the same time, user participation is a well-described state of the art (e.g. in DIN EN ISO 9241 as a route to usability). Appropriate sociotechnical use cases can be helpful in this regard [see RE 2.7-3].

Design of work organization

One of the benefits of digitalization is that the handling of information and data flows can be supported by technology, and can be changed so that information can increasingly be integrated both horizontally and vertically, and within and outside of a company. On this basis, organizational tasks can be partially or fully transferred to technical support systems. Referring back to the use case described above, these developments mean, for example, that more criteria can be taken into account when staff deployment planning than was previously possible. In addition to attendance and qualification, ergonomic aspects can, for example, be systematically taken into account in order to plan for stress changes.

Digitalization also extends the possibilities for organizational allocation of subtasks that impose a considerable physical load on the technical systems – either partially (such as in the form of a human-robot interaction) or fully (such as in the case of driverless transport systems). This will generate scope, not only to make sure that the work-related tasks taking place during the work process or value added process are more holistic, but that they can also be used for continual improvement (such as the further development of the organization). This also enables greater flexibility and room for improvement with regard to working hours or locations. For this flexibility to succeed, modifications and, in some cases, decentralization will need to made in leadership, co-determination and collaboration processes covering the entire spectrum, from presence within the company and presence in virtual spaces to limited contactability and the informational richness of the communication methods or communications media used in each case.

The use of digital technologies requires human interaction with these technologies. If interaction with technology replaces interaction with humans to a large extent, it is feared that humans could become socially isolated. This appears to be possible, for example, in mobile work, in the context of human-robot collaboration or in networked work on/with several machines. With regard to occupational health and safety, the prevention of social isolation is part of the employer's organizational duty [see RE 2.7-4].

Based on the above, the operational structure can be reconfigured by agile methods, depending on the order situation (also in the case of late change requests of the customer, for example), and even greater account can be taken of ergonomic aspects, such as age-appropriate working structures, so that the work performance and the efficiency of the workforce will improve throughout their entire working lives. Similarly, learning and qualification content can be planned according to workload and integrated into work activities, so that the dynamics of technological development can also be taken into account in terms of imparting the knowledge and skills necessary for its use. This concerns both employees and managers [see RE 2.7-5, RE 2.7-6].

The organizational structure must be designed in such a way that it enables decisions to be made quickly in view of the highly dynamic developments in the field of digitalization. Decentralized and function-oriented approaches are available for this purpose and support cooperation-oriented, project-related working methods. This also means that changes to processes may require adjustments to superstructures. The organizational structure in companies that have successfully implemented digital transformation processes will be characterized by cross-departmental working groups [see RE 2.7-7, RE 2.7-8, RE 2.7-9].

Design of tasks and activities

The use of Industrie 4.0 elements also affects the design of tasks and activities: Functions will continue to be shared between humans and/or machines. A function assignment should be made dynamic so that it can vary more flexibly. This is already visible today in socio-technical systems such as human-robot collaboration: A robot can take over work tasks of employees completely or partially (and vice versa) or an employee is supported in their work task by a robot or an assistance system in parts of this work task. Future human-system interactions will take many different forms [see RE 2.7-11].

In the future, in addition to stationary operating elements, control rooms, control stations or mobile operating systems (e.g. tablet, smartphone) for multi-machine operation will be more common. This enables machine operators to monitor, control, maintain and repair several machines simultaneously. The employees coordinate their tasks at the stationary and mobile control stations. A variable and at the same time clear assignment of task functions to machines and orders, as well as feedback on current statuses and changes are necessary for the employee.

In Industrie 4.0 work systems, processes and products are controlled in different ways by artificial intelligence or self-learning algorithms; they thus act partially autonomously. Collaborative robots or other AI-supported systems, for example, can optimize their operation independently. Informational assistance systems are used, e.g. for the preparation of experience-based task descriptions and their presentation via data glasses. Effects on the allocation of functions and also the scope of action of employees should be based on requirements for the ergonomic design of tasks and activities. [see RE 2.7-12].

Digitalization offers comprehensive technical possibilities, e.g. to support informational work with assistance systems, i.e. among other things the task-appropriate, transparent filtering and presentation or visualization of complex information. This information is obtained, for example, by a data analyst using algorithms from unstructured and multi-dimensional data (from several (sensor) sources) and then made available to a machine operator so that they can use it on machines or process it in "real" time. The design of future work tasks in Industrie 4.0 allows the employee a test run of a work process (e.g. a simulation with the administration shell, virtual reality). This allows quantitative and qualitative forecasts of target achievement as well as predictions and planning of work processes. A work sequence determined by simulation is transferred to the machine and processed there. Current solutions from the process industry will be similarly developed in the future for machines, plants or automatic machines and allow the employee to plan, decide, execute and evaluate tasks. [see RE 2.7-13].

Interactions with future networked technical systems will change the scope of action, possibly also depending on the situation. This will result in new design and qualification requirements. In contrast to fully automated industrial robots, collaborative robots enable employees to learn or teach. For example, an employee can change their tasks several times by setting up a robot for the production of a new product variant also by manual guidance. [see RE 2.7-14, RE 2.7-15].

It can be assumed that in future, the tasks of humans will involve more monitoring, checking, planning and control processes. This results in new requirements for function sharing, interaction and information provision.

Design of products, equipment and interfaces

New technologies such as data glasses, exoskeletons or collaborative robots require new concepts for the design of human-machine interfaces in relation to the respective tasks. These are currently being discussed in various standardization committees and activities (e.g. revision of the DIN EN 614 series and its planned transfer to ISO level).

In addition to the harmonized standards and specific product standards, the DIN EN ISO 9241 series of standards offers possible orientation for the design of products, work equipment and interfaces. DIN EN ISO 9241-210 describes the activities in cases where the interaction of humans and systems is characterized by a human-centric design: it requires iterative, agile procedures that regularly include the user and collect their feedback. DIN EN ISO 9241-112, on the other hand, states comprehensive principles for the presentation of information, the general validity of which extends to its application in virtual or augmented interfaces. The transferability of these principles of information presentation to products such as collaborative robots, which are characterized by physical interaction, and resulting peculiarities as well as hazards, is currently being investigated in research. [see RE 2.7-19].

Design of work environments, work spaces and work stations

The committees ISO/TC 159/SC 3 "Anthropometry and biomechanics" and NA 023-00-03 Joint working committee "Anthropometry and biomechanics" are currently discussing and developing the following topics: updating data on body sizes, the use of new technologies (e.g. 3D body scanning, digital ergonomics) to extract data, and requirements for the technologies as a prerequisite for generating safety evaluations. Adaptive equipment shall therefore enable the work station to be individually adapted to each employee. [see RE 2.7-27].

Design of work so that it promotes learning and the development of competencies

The high pace of development in the field of digitalization is creating a situation in which work tasks and, in some cases, organizational structures are changing more rapidly than ever before. As a result, the requirements humans need to fulfil (in terms of qualifications, competences and skills, etc.) are also changing at a more dynamic rate. Consequently, the importance of competences for dealing with new or changed work situations is increasing, as is the importance of continuous development of knowledge (lifelong learning) for all those involved – managers and employees. At the same time, digitalization provides a significantly broader range of opportunities to design work in a way that facilitates learning and that integrates workplace-based learning by incorporating appropriate learning situations in the work process. These include experience-based task descriptions and also the regular assignment of specific tasks so that the individual can gain a high degree of practice or is able to learn how to carry out incremental changes to the task concerned. This is deemed the way forward to align the efficiency and innovation targets that companies are endeavouring to achieve by means of digitalization with employee-related targets that are intended to ensure that work is designed in a manner that promotes skills and "on-the-job learning". [see RE 2.7-29, RE 2.7-30].

2.7.3 Recommendations for action and application

Design of the work system

2.7-1 The formulation of minimum standards for the consideration of socio-technical aspects is to be examined in various generic standards on ergonomics and work design. As referred to above, the relevant statements regarding the design of work systems are currently scattered across numerous standards. This means that operational planners find it more difficult to find them and to take sufficient account of them when planning Industrie 4.0-solutions. To this end, the overview of the relationships in ergonomics standardization should also be improved.

2.7-2 Against this background it is recommended that operational planners be provided with a document containing a summary of all process-relevant statements regarding Industrie 4.0. This should first be implemented in a guide to work system design for Industrie 4.0-solutions.

2.7-3 Socio-technical Use Cases

Work organization and design are central elements and success factors of a work system. Each use case should describe the objectives for work organization and task structure on which the use case is based and what measures are planned to implement user participation. A further core component of work system design is the task-appropriate, ergonomic design of work equipment (e.g. in accordance with DIN EN ISO 6385). Each use case should therefore describe the means by which this requirement should be implemented. Socio-technical use cases typically imply new competence requirements, it should be described in each use case how the need for competence and competence development should be determined or at least estimated in which way the design of the I 4.0-component(s) should contribute to competence maintenance, competence development and learning/development-promoting design of Industrie 4.0 work systems, and which other ways of competence maintenance, competence development and learning/development-promoting design of Industrie 4.0 work systems should be considered and designed.

It is valuable for forward-looking work design to employ use cases to describe and assess possible physical and psychological hazards and their prevention.

Design of work organization

2.7-4 A future expected, possibly even dynamic, division of functions between human and machine generates levels of action with different degrees of freedom from the autonomous functioning of the machine to a division of the respective scope of action and decision-making to the independent decision of humans. This results in the need to supplement or amend standards such as DIN EN 614-2, ISO/TS 15066 and DIN EN ISO 10218-2.

2.7-5 The management of employees will change under the conditions of Industrie 4.0. In order to organize, develop and train human-centred aspects of leadership in this context, the creation of an organizational role in companies seems helpful. Their tasks include creating acceptance for Industrie 4.0 in the company and deriving a digitalization strategy from the company's vision and mission. DIN EN ISO 27500, ISO 9241 ff and ISO 26800, for example, require additions or amendments.

2.7-6 Large scale data collection, storage and processing will be an essential part of Industrie 4.0. Safety targets in this context include availability, integrity, confidentiality and legally compliant handling of the data. DIN EN ISO 27500, ISO 9241 ff and ISO 26800, for example, require additions or amendments.

2.7-7 The increasing possibilities of organizing work independently of time and place are leading to a further spread of mobile work. Its design options differ substantially from those of stationary work. DIN EN ISO 9241-1:1997 for example, requires additions or amendments.

2.7-8 The progressive automation and mechanization of work organization can lead to a reduction in interaction processes between people. Care must be taken to identify and assess aspects of social isolation in terms of their potential impact on the mental stress of employees. There is a need to supplement or amend the following standards: DIN EN ISO 10075-2, DIN EN ISO 10075-2, DIN EN 6142.

2.7-9 The continuous adaptation of work organization to technical developments requires an adaptive learning and qualification behaviour of employees. Lifelong learning must be supported by work design that promotes learning. DIN EN ISO 27500, ISO 9241-11, -20, -100, -171, and -210, ISO 26800 and DIN EN ISO 10075-2, for example, require additions or amendments. In addition, a guideline on this topic is being developed by VDI Technical Committee 7.22.

2.7-10 The understanding of an organization and its environment should be expanded due to the changing context in Industrie 4.0 or extended framework conditions. Processes that may run purely digitally require that the virtual environment of an organization also be considered. DIN EN ISO 9001:2015 for example, requires additions or amendments.

Design of tasks and activities

2.7-11 Interactions between human and machine/plant should be able to be designed dynamically with regard to gradations of tasks, interactions and information. At these levels there are actions of varying degrees, e.g. from the automated functioning of the machine to a division of actions to the complete and sole action of humans. DIN EN 614-2, DIN EN 894-1,3, ISO/TS 15066, DIN EN ISO 10218-2, DIN EN ISO 29241-2, DIN EN ISO 10075-2, DIN EN ISO 11064-1,5,7, DIN EN ISO 13861, C standards on machines, for example require amendment.

2.7-12 In the future, technical systems will be automated, and in the short-term and dynamically adapted to production processes. Reconfiguration processes influence the human-machine function division and should therefore be mapped as adaptable automation. DIN EN 614-2, DIN EN 894-1, DIN EN ISO 29241-2 for example require amendment.

2.7-13 In the future, lifelong learning and digital literacy will become more important. New possibilities of technical support for employees' qualifications enable them to perform other and more varied tasks. As a result DIN EN ISO 27500, DIN EN ISO 9241-11,- 20, -100, – 171, and 210, DIN EN ISO 26800, DIN EN ISO 10075-2 require amendment.

2.7-14 In future, it must be taken into account that machines and other technical systems should also be able to recognize descriptive characteristics of humans (e.g. height, posture, facial expression) and adapt to them. In response, humans change their behaviour. This results in new requirements for the design of tasks and activities. DIN EN ISO 6385, DIN EN 614-2, DIN EN 894-1, DIN EN ISO 29241-2 for example require amendment.

2.7-15 Human-system interfaces must be designed to be distinguishable for several employees working in parallel, for several machines and for different products and quantities. The requirements for ergonomic task design should take into account that, in future, interfaces will have to be designed for several machines, several stationary and mobile control and monitoring units, several processes running on them and use by several employees simultaneously. This recommendation is necessary not only for the design of the task interface, but also for the design of interaction and information interfaces. The series DIN EN ISO 9241, 10218 and 11064 and DIN EN 614 and 894, C standards for machines, for example, require amendment.

2.7-16 Future work tasks should enable employees to test run a work process (e.g. a simulation with the administration shell, virtual reality). Changes result from the ergonomic design of tasks through trial treatment, through subsequent real implementations and through changed design requirements for work organization and workplace. The series DIN EN ISO 11064, 894 and 9241, and DIN EN 614-1 and -2, C standards for machines, for example, require amendment.

2.7-17 Assistance systems can specify the sequence in which tasks are to be processed or the system behind it, in terms of operational organizational objectives such as route optimization, time savings, order of tasks, etc. The interface design should allow the employee to decide when to accept the next job, how to carry out the next job, etc. The employee must have control over the process and be able to decide. DIN EN 614-2 and DIN EN ISO 10075-2, C standards for machines, for example, require amendment.

2.7-18 Feedback from an (assistance) system to the operator must be adapted to the task in terms of status, structure, process and content. The first thing to do is to design the tasks. The indication design follows the task design and is oriented to it. DIN EN 894-2 and DIN EN ISO 11064-1, and standards on the design of assistance systems, for example, require amendment.

Design of products, equipment and interfaces

2.7-19 Work processes with assistance systems in the context of Industrie 4.0 challenge employees through monitoring and control activities which, in contrast to normal work, cannot be interrupted at any time and which influence the control possibilities through their own dynamics. The DIN EN 894, DIN EN ISO 9241, DIN EN ISO 11064 series require amendment.

2.7-20 In the context of Industrie 4.0, static to dynamic interactions and information representations will be designed with suitable interfaces. Work systems with self-dynamic components of technical systems also require dynamic interactions and information. The following standards require revision: The DIN EN 894 series, DIN EN ISO 9241-110, -112, DIN EN ISO 11064-5.

2.7-21 Design requirements for interfaces for interactions with potentially dangerous or safety-critical systems go beyond usable design, since the latter do not address relationships to safe (in terms of functional safety, IT security and reliability) design. Relevant standards to be examined are: DIN EN ISO 13849-1, 2, DIN EN ISO 26800, DIN EN 894, DIN EN ISO 9241-11, -210. For the application context of machine design it is necessary to explain and take up a reference to such design objectives.

2.7-22 The simple representation of complex information should be supported for machine operators in the context of Industrie 4.0, so that quantities of information that can be processed by the machine operator can be selected and a machine can visualize the data depending on the selected quantity (selection of relevant standards: e.g. DIN EN ISO 9241-112).

2.7-23 The use of autonomous or fully automated processes and products in work systems should be transparent for employees. Interactions should be predictable and comprehensible and enable an adequate situational awareness of the employees. This can be achieved, for example, by providing notices, advice and explanations. (Interaction and general behaviour are not always predictable, it depends entirely on the state and situation. But these states and situations can be simulated with given semantics).

The following standards need to be revised, for example DIN EN 894-1, ISO/TS 15066, DIN EN ISO 10218-2, standards on Artificial Intelligence (ISO/IEC JTC1 SC42) and on self-learning algorithms (see Chapter 4.1).

2.7-24 Need for adaptation in case of the requirement "presentation of complex information"
The information should be provided in such a way that the respective amount of information can be selected by the machine operator and the information is visualized close to the machine. This form of human-machine interaction refers, among other things, to different tasks (e.g. assembly, monitoring) and operating modes (e.g. maintenance, troubleshooting, servicing). The ergonomic design of information should be geared to the required presentation and processing. The following standards, for example, require adaptation: DIN EN ISO 9241-112, DIN EN 894-1.

2.7-25 The process of teaching collaborative robots by employees should be ergonomically designed (e.g. expectation-compliant, error-tolerant and self-describing). ISO/TS 15066, DIN EN ISO 10218-2 require revision, for example.

2.7-26 Requirements for exoskeletons must be made more concrete in standards. No relevant standards are yet available, new projects should be initiated.

2.7-27 The use of body-supported assistance systems such as exoskeletons can reduce energy-intensive activities. New risks for the one-off or varying long and short-term use of such systems should be avoided. DIN 33411 and DIN EN 1005 require revision, for example.

Design of work environments, work spaces and work stations

2.7-28 The possible use of new technologies such as exoskeletons, data glasses or mobile robots, driverless transport systems (see Use Case) should be taken into consideration when designing the work space and work station; new requirements for traffic and escape routes, for example, arise.

Design of work so that it promotes learning and the development of competencies

The developments outlined, which, in part, are highly dynamic, and the developments that are currently in progress provide a variety of approaches which standardization is recommended to take.

2.7-29 When constructing and designing the technical systems, and in particular when designing human-machine interfaces, aspects of the design that will facilitate learning must be taken into account. It is a case of looking ahead and taking account of the operational processes (control and information processes, and communication and feedback processes).

2.7-30 Procedures that will enable the establishment of lifelong learning should be defined as part of the continual improvement process (and/or existing specialist knowledge should be updated by means of incremental learning).

3 Need for standardization on cross-cutting topics

3.1 Open Source

3.1.1 Status and progress since Version 3

Open source is gaining in significance in association with standardization, in the area of Industrie 4.0 as well. In a way similar to standards and specifications, open source takes the form of open technologies that are developed during the course of collaborative processes and are provided for use by all market players. Accordingly, the subject has also been included as an objective in the new German Standardization Strategy (DNS, see **Chapter 1.1**): DIN and DKE are establishing partnerships and looking for ways to cooperate effectively with open source projects and to use open source technologies and methods in standardization. To achieve this goal, DIN has launched an initiative to establish partnerships, and DIN and DKE are also participating in similar projects at CEN-CENELEC and ISO/IEC.

Nevertheless, open source must not be regarded as equivalent to, or be confused with, standardization. In open source projects, source code is collaboratively created and software is developed, which is then made available to the market as open source software. Publication is subject to certain license conditions that have been established on the market over the years and that are tailored to the specific conditions and requirements of open source projects. Those who want to use open source software or even change or extend it, have to take a closer look at these different license conditions, because they define what the user is allowed to do with the software.

An important term in this context is the so-called copyleft, by which open source licenses are categorized. Strong copyleft means that all changes and further developments of an open source software may only be distributed under the same license. Besides strong copyleft (licenses that do not allow any deviation from this principle), there are also less restrictive ones (weak copyleft) and those that do without copyleft altogether (see **Table 1** with a selection of examples). If the user wants to extend different open source software to a new software, they have to make sure that the licenses can be combined in one source code. For example, they could not use the source code from a GPL project in an Eclipse project.

Open source projects supplement standardization in various ways.

- The standard/specification is implemented in open source software: Open source is increasingly a way to quickly position technologies on the market – including the standards and specifications that are implemented in open source (example: open62541/ Eclipse Milo).
- The specification is developed as part of an open source project: In the field of interoperability interfaces and similar interoperability technologies, developments are taking place in open source, which on the one hand, as explained above, are directly available to the market in open source form or, on the other hand, flow back into standardization.
- The joint development of consensus-based standards and their implementation in open source format: In addition to the dissemination of technologies via open source, information on functionalities and in particular on functional gaps flows back into standardization, on the basis of which standardization can react very quickly and specifically. An example of this type of procedure is the "Agile Standardization" approach presented in **Figure 27**. This approach is also followed by LNI 4.0 through testing and validation to

provide feedback to standardization (example: AASX Package Explorer, BaSys/BaSyx) [see **RE 3.1-1**].

Table 1: Copyleft categories with examples of licenses

Strong copyleft	Weak copyleft	No copyleft
→ GPL (General Public License)	→ LGPL (Lesser GPL) MPL (Mozilla Public License) EPL (Eclipse Public License)	→ Apache 2.0 BSD (Berkeley Software Distribution) MIT (Massachusetts Institute of Technology)
For all modifications and further developments of a software the same license conditions apply as for the original code, i.e. these must also be made available in source code. GPL plays a special role because Linux was written under it. In general, copyleft licenses for commercial use have tended to decline.	In order to promote the distribution of free libraries, a weakened copyleft license was created with the LGPL. It allows the linking of free and proprietary software. This category also includes MPL and EPL. Here, changes to existing code are subject to copyleft, but independent extensions and new developments may be distributed under a different license.	These free – also called permissive – licenses do not prescribe under which conditions changes and further developments must be passed on, i.e. they can be licensed as open source or proprietary. A special feature of the Apache 2.0 license is that it explicitly stipulates the granting of patent rights for use, modification or distribution.

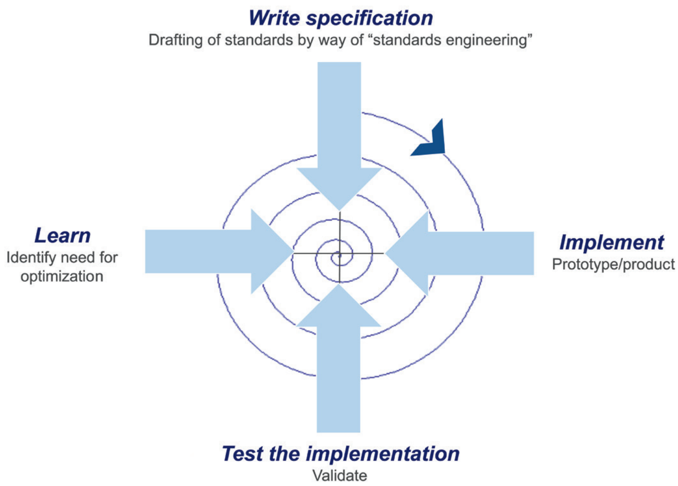


Figure 27: Agile standardization

3.1.2 Current developments

In the following, current open source technologies and projects are presented that are of direct relevance to Industrie 4.0 and are closely related to standardization:

Project: open62541/Eclipse Milo
In **Chapter 1.4.1** on the **Use Case 2** "Standardization of the manufacturing characteristics of machines" the standard OPC UA was discussed and it has been referenced repeatedly in the further course of the Roadmap. This standard was published as the

IEC 62541-100:2015 series of standards, and there are a number of relevant open source implementations. Reference is made here to open62541 implemented in C and Eclipse Milo which is implemented in Java. Eclipse Milo is licensed under Eclipse EPL-2.0 and open62541 is licensed under Mozilla MPL-2.0. Both are weak copyleft licenses, so that the libraries could also be used in proprietary software if they are not modified. The projects can be downloaded via GitHub.

Project: AASX Package Explorer
The AASX Package Explorer is a sample implementation as an open source project for administration shells (see **Chapter 2.3**). With this software tool, administration shells can be created and edited and can be easily exchanged with each other. The AASX Package Explorer implements the central specification "Details of the Asset Administration Shell – Part 1" for Industrie 4.0. The tool creates administration shells in the formats XML and JSON and stores them with the other files in an AASX container. Concept descriptions with ecl@ss IRDIs are automatically created and referenced. With import and export functions for e.g. BMEcat, AutomationML or OPC UA, other data formats and real company data can be integrated very quickly. The AASX Package Explorer is licensed under Eclipse EPL-2.0 and can be downloaded via GitHub [91] .

Project: BaSyx
The BaSys 4.0 research project was concerned with the development of a basic system for production plants that realizes the efficient changeability of a production process. The concepts developed within the project were implemented in the open source project BaSyx. BaSyx implements a middleware that implements administration shells, communication services and submodels for service-based production. In BaSyx services for registry and discovery are defined, which serve as a basis for part 2 and part 3 of the administration shell in detail. BaSyx provides SDKs to simplify implementation in the programming languages Java, C++ and C#. BaSyx is licensed under Eclipse EPL-2.0 and can be downloaded via GitHub [92]. The follow-up project BaSys 4.2, which focuses on the further development of the BaSyx middleware with regard to the continuous engineering of production processes, started in mid-2019.

Technology: Distributed Ledger/Blockchain
Version 3 of the Standardization Roadmap presented the Distributed Ledger Technology/ Blockchain (DLT/BC), which is developed as an open technology in open source projects such as Hyperledger. It is above all a standardization of this technology for industrial use that is needed, which is currently being worked on in various standardization organizations. Special reference is made to DIN NA 043-02-04 AA: Blockchain and technologies for distributed electronic journals, mirror committee to ISO TC 307, but a good overview of these activities can be found in chapter 4.4 of the "Blockchain Study: Automation and Digitalization" of ZVEI [93].

At this point, it should be noted that the first marketplaces for data based on this technology are emerging. For example, there are approaches to use administration shells for the interaction between value creation partners with block chains. Data from IoT devices can be sold via such marketplaces, vehicle data can be recorded securely, and machines from different manufacturers can be networked.

In addition to the projects mentioned above, initiatives for cooperation within standardization with open source have been launched at DIN and DKE as well as at CEN-CENELEC to pilot cooperation within standardization with open source. At CEN-CENELEC, a pilot project on eInvoicing was launched within CEN/TC 434. Parallel to the standardization work, experts from the Technical Committee have developed open source validation software. The pilot project will examine to what extent the software can be recognized by CEN-CENELEC as a result of the Committee's work and what rules must apply. The group is also analyzing which form of publishing and development is best suited for collaboration with open source communities.

The JRC study "The relationship between Open Source Software and Standard Setting", which makes recommendations for standards organizations, and the report of the IEC SMB ahG 76 Masterplan Implementation – "New ways of working" also provide indications of necessary changes to the framework conditions [see **RE 3.1-2**].

3.1.3 Recommendations for action and application

3.1-1 It is recommended to further develop agile standardization through pilot projects and thus to strengthen the cooperation of standardization with open source. Specifications (e.g. DIN SPEC or VDE SPEC) within the framework of Industrie 4.0 provide a good opportunity for piloting.

3.1-2 In order to accelerate the dissemination of Industrie 4.0, the development of sample implementations as open source should be promoted even more strongly. With the help of license recommendations and legal opinions it has to be ensured that the use, and especially the participation, in open source projects is easily possible.

3.2 Industrial Security

3.2.1 Status and progress since Version 3

Information security represents a firmly established industrial and social value. It is a basic requirement for Industrie 4.0 and trustworthy cooperation within digital ecosystems. Despite all the challenges involved, it creates the high level of trust in Industrie 4.0 worldwide and is an important aspect of trustworthiness along the value chains. This chapter focuses on the topic of security in the sense of "industrial security", i.e. the holistic protection of information technology in production systems, as well as of machines and plants against sabotage, espionage or manipulation. In this sense, data protection (privacy) and functional security are typical protection goals of industrial security. These topics are dealt with in **Chapter 3.4** and **Chapter 3.5**.

Future standards must be compatible with regulatory requirements, which can be both national (see "**German IT Security Law**") and European in origin. In particular, the "European Cyber Security Act" aims to define an EU-wide cyber security framework for the EU-wide certification of digital products, services and processes through uniform regulation, thus creating the prerequisites for a European "Digital Single Market" for products with comparable security levels. In particular, the relationship between the New Legislative Framework (NLF) and the EU Cybersecurity Act will have to be assessed in the future. The core concept of the NLF is to specify only the essential requirements for products in the relevant European directives, whereas the technical framework conditions are specified in harmonized standards. The EU Cybersecurity Act does not yet explicitly address the NLF itself, so that the interaction between the two regulatory approaches needs further clarification. This requires constructive and comprehensive coordination between authorities, legislators and standardization organizations in a timely manner. International standardization activities that support future certifications in the field of industrial security are taking place in particular in IEC/TC65, IECEE CMC WG31 and ISO/IEC JTC1/SC27. [see RE 3.2.1].

In the meantime, the development principle "Security by Design" is generally accepted for industrial security. The consequence of this is that security functions are integrated into the planning, development and manufacturing process from the outset, which means that appropriate process and product standards, as well as requirements and certification standards are particularly necessary.

Since the publication of the Standardization Roadmap Industrie 4.0 Version 3, important new developments have taken place, particularly in the area of industrial security and data protection.

Therefore the realization is that classically available security solutions from the IT and office areas are unsuitable or insufficient for industrial applications. The various security requirements are determined in particular by real-time and robustness requirements (see Chapter 2.6), life cycles of industrial components (see Chapter 2.3.1), and requirements for the continuous availability of industrial plants.

At the same time, it is essential for industrial security to implement end-to-end security architectures that cover both the IT areas and the OT areas of a company (or an entire Industrie 4.0 application scenario).

This led to various/numerous initiatives for the definition of security standards with the special aspect/boundary conditions of industrial suitability to be applied along the value creation chain (IEC/TC 65, ISO TC 292). It can be observed that there is an ever increasing need to protect industrial applications and systems directly (i.e. at application level) rather than relying on network security mechanisms alone. In this way, end-to-end security or, for example, measures for know-how protection, licensing protection or data protection can be implemented.

The communication between I 4.0-domains across public areas must be able to be protected by industry standard security mechanisms. The security of the communication of devices, machines and systems across company boundaries must be controlled and guaranteed by the involved parties, independently of the (external) telco provider of the I 4.0-partners.

Especially the protection of applications supported by artificial intelligence mechanisms creates new requirements: Here, security functions should ensure that an application delivers exactly the functionality that the user expects in terms of trustworthiness, without the result being falsified by wilful manipulation of input data or function components. As a result, the classic integrity protection of data or components and systems is faced with completely new challenges (see ISO/IEC JTC 1/SC42).

For industrial security, the expectation of trustworthiness has become increasingly important along the value creation chain. This makes protection and proof of the integrity of data, systems and processes along a "supply chain" of high importance, which will be reflected in future standards (ISO/IEC JTC1 WG13).

In addition to ensuring interoperability and comparability of safety levels, future standards should also contribute to overcoming implementation obstacles (ISO/IEC JTC1/SC41).

Such "perceived" obstacles are:

- unclear contribution of security investments to value creation: In certain sensitive areas such as critical infrastructures, however, government regulation will increasingly force the implementation of appropriate measures
- lack of a global trust infrastructure, which, for example, offers the possibility of globally consistent encryption of the transmission of communication and control data
- the lack of generally applicable and industry-compatible implementation standards with moderate certification efforts for trustworthy solutions
- lack of assessment of the trustworthiness of value creation networks in Industrie 4.0 with regard to data protection requirements [see RE 3.2-10]
- fear of increased system complexity due to security measures that cannot be dealt with in conventional established processes for development and operations [see RE 3.2-11]

3.2.2 Current developments

Work on I 4.0-relevant security standards has commenced and in some cases been completed (see Annex BB) in the following committees in recent years (since the publication of the Standardization Roadmap Version 3), and has been addressed in new working groups/committees (with adapted scope/extensions).

- DIN, DKE and CEN-CENELEC: mirroring the international bodies in IEC, ISO and ISO/IEC JTC1
- IEC/TC 65/WG10: Standardizing IEC 62443
- IEC/TC 65/SC 65E/WG 8: OPC: Client/server SW Interface inclusive security
- IEC/TC 65/WG 23 Taskforce Cyber Security: Identify cyber security relevant smart manufacturing scenarios and requirements
- IECEE CMC WG31 Cyber Security Certifications
- ISO/TC 292/WG4: Authenticity, Integrity & Trust for Products and Documents/Anti-counterfeiting
- ISO/TC 292/WG8: Supply Chain Security
- JTC1/SC27/WG3 Security evaluation, testing and specification
- JTC1/SC27/WG4 Security controls and services
- JTC1/SC 31 "Automatic identification and data capture techniques"
- JTC1/SC 41 Internet of Things and related technologies
- JTC 1/SC 42 Artificial Intelligence
- JTC1/WG 13 Trustworthiness

3.2.3 Recommendations for action and application

3.2-1 Harmonization of the EU Cybersecurity Act and New legislative Framework
A constructive and comprehensive coordination among authorities, legislators and standards organizations regarding the interaction of the two regulatory approaches of the EU Cybersecurity Act and the New Legislative Framework should take place promptly.

3.2-2 Security infrastructure for secure inter-domain communication
Secure communication requires secure identities (identifiers and attributes) and anchors of trust. Generating and administering secure identities and securing their trustworthiness require a secure infrastructure. The requirements for this include factors such as scalability, resilience, profitability, long-term fitness for purpose, and (user-defined) trustworthiness beyond local legal jurisdictions and independent of local jurisdictions.

Cross-domain governance structures to support secure Industrie 4.0 communication must be defined and standardized. This will require the close cooperation of all industrial stakeholders. The possible use and integration of national and regional solutions (such as eIDAS) must be examined with the help of the regulatory authorities and tested in field trials/pilot projects.

3.2-3 Security for agile systems
Definition of standards for technical negotiation of security profiles (based on capabilities and properties) for Industrie 4.0 communication or cooperation of entities in different security domains.

This includes the:
- → Identification and authentication of the partners involved (requirements and solutions)
- → Evaluation of the degree of trustworthiness of cooperation partners
- → Technical support for information classification and requirements for handling appropriately classified data
- → Especially when using AI methods: their quality must be ensured; methods of assessment are important and must be developed (research)
- → Topic quality certificates
- → Definition Trustworthiness Profile, – Capabilities, Supply Chain, Traceability, (Cloud Trustworthiness); JTC 1/SC41, Trustworthiness Framework.

3.2-4 Methods for determining the security characteristics of composite products based on the security characteristics of the contained/interacting components.
The security characteristics of a system are determined by the corresponding characteristics of the components (SW as well as HW) and their configuration in a complex, mostly non-linear way. More detailed research is required into this issue and should be made more accessible once standardization work has reached a suitable level of maturity.

3.2-5 Access, roles and authorization mechanisms for Industrie 4.0
Access to and use of data and resources within the framework of Industrie 4.0-cooperations requires standardized rules. Existing concepts, such as IEC 62351, can serve as a starting point. Boundary conditions governing implementation include scalability and the potential for representation in the form of specific vertical requirements.

3.2-6 Security standards for the exchange of type and instance information of administration shells

Online and offline options are provided for the exchange of type or instance information. A data format for transfer files is proposed. Mechanisms for ensuring authenticity and confidentiality must be defined and established as global standards. Access APIs are to be defined. This must be coordinated with the concepts for secure identities (see [RE 3.2-2]) and access control (see [RE 3.2-5]).

3.2-7 Standardized security development process for integrators and operators

IEC 62443-4-1 defines a security engineering process for component suppliers; this must be expanded to take into account the other parties that form part of the value creation network, such as operators and integrators, in order to make it possible to implement comprehensive and consistent security architectures within the sense of "security engineering".

3.2-8 Generic interface for security elements in embedded systems

The implementation of cryptographically based security functions in I 4.0-devices must be protected against attacks. High security levels can be achieved by integrating suitable security hardware. However, the diversity and complexity of the assemblies available on the market with their special boundary conditions leads to high integration costs and thus to a relatively high application threshold for manufacturers and integrators, especially for SMEs. A "*Generic Trust Anchor API*", which would be supported by many hardware manufacturers as a uniform programming interface, can provide help.

3.2-9 5G Security for Industry

The fifth generation of mobile communications (5G) is intended to meet a wide range of availability, security and capacity requirements. Data and its transport between data source and data sink can be dynamically modified and processed. The network is thus becoming intelligent. In the ISO-OSI model the 5G technology can therefore be located at all levels 1 to 7.

5G technology and its use can be clustered:

- → Installation of 5G components as part of product development
- → Local use of 5G on site and operation by one's own organization
- → Use of 5G services provided by mobile providers

New features and possibilities of 5G require the possibility of dynamic, flexible and scalable security architectures. On the basis of suitable industrial use cases, it must be possible to derive the security requirements taking into account existing security standards such as ISO/IEC 27001 and IEC 62443 within the framework of the 5G standard.

- → Industrial security guidelines must be implementable, especially for I 4.0-based cross-company communication.
- → Application of IEC 62443 and ISO/IEC 27001 must be possible, especially in in-house operations.
- → The protection of metadata of the communication of devices, machines and plants must be guaranteed. This applies in particular to data that can be collected by the telecommunications provider via the signalling channel.
- → Industry-compatible security requirements should be actively incorporated into the 5G standardization process.

3.2-10 Industrie 4.0 Security Management Processes

The increasing networking within the framework of I 4.0 requires coordinated and cooperative processes and standards for security management, which can interact across domains. This includes the:

→ Support of security management for dynamically reconfigurable automation systems (plug and automate)
→ Integration of the digital twin in security management
→ Secure dynamic patch management
→ Uniform, machine-readable format for vulnerability information
→ Continuous compliance monitoring
→ Resilience, business continuity
→ Security event handling
→ Supply chain security

3.2-11 "Security Training" guide

IT security aspects must already be considered in the planning and development phase of products and systems ("security by design"). Employees in production need additional IT security knowledge, as production and IT worlds merge and competence requirements fundamentally change.

Essential organizational and process-specific security aspects must be considered in the corresponding standards for their implementation. Suitable guideline standards for "security training" must be derived from this.

3.3 Data protection/privacy

3.3.1 Status and progress since Version 3

The protection of personal data benefits not only the individual but also society as a whole: People who know what happens to their data and have an influence on it can handle digitalization more confidently. In the context of industrial processes, data protection has so far mainly occurred as employee data protection, because digitalized processes and systems collect data on employee activities and these can also be used for performance monitoring. Industrie 4.0 expands the field of application because business-to-consumer aspects and systems are linked to industrial manufacturing systems. This is most obvious in the industrialized production of custom-made and/or individualized products (batch size 1). Examples are dental prostheses, the production of which requires a large amount of personal health data, or individualized clothing, for example, which is printed with private, individually created photos. In both cases, personal data that must be protected is transferred to the manufacturing systems.

Accordingly, standards must be compatible with regulatory requirements and should support them. In scientific discourse, the term or implementation "...by design" is now generally accepted as a development principle for the topic of privacy, as it is for security. This also means that privacy functions must be successively integrated into the development and production process from the outset, which means that appropriate process and certification standards are also required for privacy. In data protection standardization, especially in ISO/IEC JTC 1/SC 27/WG 5, this principle has already been reflected in standards projects and "standing documents".

Since the publication of the Standardization Roadmap Industrie 4.0 Version 3, important new developments have taken place, particularly in the area of data protection. Based on the recommendations for action formulated at the time, these are:

The EU's General Data Protection Regulation (GDPR) came into force in May 2018. It not only contains requirements in the area of privacy by design, but also has an effect beyond the marketplace principle, namely everywhere EU citizens meet service providers as recipients of services. This also affects suppliers based outside the EU. Accordingly, international standards are being developed by ISO/IEC JTC 1 and ISO.

Applications of artificial intelligence mechanisms pose further problems, which also concern data processing and big data. Data protection compliance in particular is made increasingly difficult by this topic, as more and more applications (especially in the area of machine learning) depend on working with comprehensive data sets, which runs counter to basic principles of current data protection law, such as data economy/data minimization and the purpose limitation principle. Furthermore, AI applications often change their behaviour, for example because they "learn". This makes security evaluation and also data protection risk assessment difficult or impossible.

Devices of the "Internet of Things" are arriving in private households, both as household appliances and as toys (for children and adults alike). Many of these devices require contact with the manufacturer or a "cloud" service provider as a matter of principle, or to extend their range of functions and deliver data to them from the household. So far, this has been particularly noticeable in toys, such as the Cayla doll, which responds "intelligently" to children's questions by passing them on to a speech recognition system on the Internet and obtaining the answer. Other toys, such as robots with cameras deliver "pictures from the children's room" to the respective contact partners or platforms. The reference to Industrie 4.0 results from the trend towards "servitization": Previously isolated devices use networked services and deliver data to them. Often the corresponding interfaces are not or are only insufficiently documented and secured. At the same time, for resource reasons, primitive and insecure protocols, such as Telnet, are being "resurrected", which increases the protection problems.

3.3.2 Current developments

Work on standards on privacy in the context of Industrie 4.0 has been started and partly completed in the following committees in recent years (since the publication of the Standardization Roadmap Industrie 4.0 Version 3) and has been addressed in new working groups/committees with adapted scopes/extensions.
DIN and DKE: mirroring the international bodies in IEC, ISO and ISO/IEC JTC1
- → ISO/IEC JTC 1/SC 27 "Information security, cybersecurity and privacy protection"
- → ISO/IEC JTC 1/SC 27/WG 5 "Identity management and privacy technologies
- → ISO/PC 317 "Consumer protection: Privacy by design for consumer goods and services"

- → CEN-CENELEC/JTC 13 "Cybersecurity and Data protection"
- → CEN-CENELEC/JTC 13/WG 5 "Data Protection, Privacy and Identity Management"

Current work focuses on process-oriented privacy standards and standards that enable privacy for users and consumers.

3.3.3 Recommendations for action and application

3.3-1 Trustworthiness of value-added networks
Definition of process standards for the protection of personal data within value-added networks up to the protection of personal data required for individualized products with batch size 1, including:
- → Rules for classifying data and information, also in the respective context (contexts are very relevant because they massively influence the sensitivity and meaningfulness of data, e.g. an article number in an Internet order seems harmless until it can be linked to e.g. a drug product database, which then shows that the product is e.g. a cancer drug or a psychotropic drug. The knowledge that the format of the article number indicates a medical device is also significant).
- → Rules for the exchange of classified data and information (which data may be passed on where under which circumstances, what the recipient may do with it, when it must be deleted, if necessary);
- → Methods of evaluating the trustworthiness of cooperation partners. Examples of mechanisms are manufacturer declarations, certificates, auditing

3.3-2 Auditing in line with data protection regulations
Definition of standards for auditing processes that process personal data and/or work at risky interfaces in a manner compatible with data protection, including
- → Methods for data-saving (e.g. aggregated) logging
- → Methods for local processing and evaluation of sensitive data so that they can be aggregated or deleted afterwards.

3.3-3 Relationship between data protection standards and Industrie 4.0 scenarios
The fitness for purpose of existing standards that relate to Industrie 4.0 scenarios must be clarified.
- → In the case of automated communication across domain boundaries (e.g. as the boundaries between jurisdictions), the relevant data protection requirements and associated security requirements derived from them must be harmonized.
- → Access control standards must be able to manage resources in a domain-oriented manner in order to ensure that the respective level of data protection is taken into account, especially for cross-border data transfers in the value chain, for example from the EU to third countries whose level of data protection has or has not been recognized as being equivalent to that of the EU, especially since such recognition can be granted or withdrawn. The domain-oriented administration of access control standards must functionally cover these recognition dynamics. Data protection standards must apply to "intelligent" home appliances (household appliances, toys, etc.) produced in Industrie 4.0-processes and their communication needs (including back to the manufacturer).

3.4 Trustworthiness of the value-added networks

3.4.1 Status and progress since Version 3

The term trustworthiness is of increasing importance in various standardization activities and is used in different committees in different contexts. The Advisory Group ISO/IEC JTC1 AG7 had taken on the task of reviewing the mutual status of work for the SCs in JTC1, JTC 1/WGs, other ISO and IEC committees and SDOs and deriving a common definition for JTC1. In the meantime JTC1 AG7 was terminated and JTC1 WG13 "Trustworthiness" was founded.

According to JTC1, "trustworthiness" corresponds to the ability to meet the expectations of the affected "stakeholders" in a verifiable manner. Trustworthiness may concern characteristics such as reliability, availability, resilience, security, privacy, safety, accountability, transparency, integrity, authenticity, quality or usability. According to JTC1, trustworthiness can apply as an attribute for products, technologies, services, data and information, as well as in the context of governance of organizations. For Industrie 4.0, trustworthiness is particularly important along the value chain: A manufacturer wants to give their customer a quality promise for one of the characteristics mentioned (e.g. security), but is also dependent on the assurance of quality by their own suppliers. Strictly speaking, a manufacturer can only guarantee quality assurance for their own added value on the I 4.0-component/Industrie 4.0-system. To assess the quality of the supplied parts/components, they need comprehensible and provable criteria.

Accordingly, "trustworthiness" forms the basis for decisions on the use of a supply/component or a device/system, or also for cooperation within the framework of a business relationship (e.g. conclusion of contracts or also hiring of employees). These are always risky decisions that are ultimately made above a basis of verifiable/provable facts. This creates two lines of action for (future) standardization:

- → To keep the basis of verifiable facts as high as possible, for example through process or certification standards.
- → To organize the risky process above this basis.

Verifiability mechanisms are particularly important for authenticity and integrity. However, every classical control of a logistics chain before delivery (="upstream") is naturally limited in terms of effort or data protection/privacy of the business partners: Which supplier wants to fully disclose their business case to their customer. However, digitalization within the framework of I 4.0 will open up new application possibilities for methods such as track & trace or distributed ledgers, which will also lead to standardization projects. General management processes for security in the supply chain are also of great importance, as are all associated standardization activities; trustworthiness concerns all phases of a use case over the entire life cycle, from the drafting of contracts to the decommissioning of a product. In the latter case, for example, it is important to prevent unauthorized re-use (e.g. of secure identities, or even of contaminated components) outside a controlled recycling process. In the case of critical infrastructures or consumer protection, standardization projects will have to be coordinated with national and international regulations.

3.4.2 Current developments

One focus is the work at JTC1 WG 13, other activities exist within JTC1 in various SCs, and in ISO TC 292, IIC, ZVEI, VDMA, I 4.0-projects with Japan and NIST.

3.4.3 Recommendations for action and application

3.4-1 Definition of process standards for the trustworthiness of collaboration within an I 4.0 value-added network.
These include:
→ the standardization of "Trustworthiness Capability Profiles"
→ methods of evaluating the trustworthiness of cooperation partners. Examples of mechanisms include: manufacturer declarations, certificates, auditing
→ rules for the exchange of classified data and information
→ minimum security requirements for B2B
→ integration of processes and components
→ compliance with regulatory provisions

3.4-2 Assessment in relation to data protection requirements
The trustworthiness of the Industrie 4.0 value-added networks should be assessed in relation to data protection requirements.

3.5 Functional safety

3.5.1 Status and progress since Version 3

With regard to the safety of machines and plants in the context of Industrie 4.0, the aspects of product and operational safety must be considered. The design and evaluation of the safety of machines and plants is a fundamental, complex undertaking which must be carried out taking into account all applicable regulations and hazards. IEC Guide 116/CENELEC Guide 32 refers e.g. to basic hazards, which are also to be considered with regard to Industrie 4.0 use cases.

The frequently referenced functional safety (according to basic standard IEC 61508) [94], as a measure for risk reduction (particularly in the machine environment IEC 62061 or ISO 13849), has a natural proximity to techniques in the context of Industrie 4.0 through its use of software and programmable hardware, but is only a sub-area of plant and work safety.

Functional safety is an important component of risk reduction. The aim of functional safety systems is to reduce the operational risk of a facility in cases where it is too high to fall below the acceptable operational risk (marginal risk). The requirements for functional safety systems cover all life cycles of a facility, from initial design considerations to decommissioning and disposal of a facility. The functional units to be considered in connection with functional safety cover the entire range of functions required for risk reduction, including actuators, logic processing (control), sensors and all necessary interfaces and installations. In addition, function-restricting external influences, such as failure of the auxiliary power supply (electrical, but also hydraulic and pneumatic) must be taken into account.

In accordance with the subject matter, the standards on functional safety require compliance with various methods and strategies for controlling faults within systems for use as safety devices on machines and plants. With regard to functional safety equipment, the basic principle is that a risk reduction derived from the respective application must be achieved, irrespective of the technology selected for the respective application.

Selected existing safety standards with functional safety requirements are
- → DIN EN ISO 12100: Safety of machinery – General principles for design – Risk assessment and risk reduction
- → IEC 61508-1: Functional safety of electrical, electronic, programmable electronic safety-related systems
- → IEC 61511-1: Functional safety – Safety instrumented systems for the process industry sector
- → ISO 13849-1: Safety of machinery – Safety-related parts of control systems
- → IEC 62061: Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems
- → IEC 61131: Programmable controllers
- → ISO 13850: Safety of machinery – Emergency stop function
- → DIN EN 50156-1-03; VDE 0116-1-03: Electrical equipment for furnaces and ancillary equipment
- → ISO 23125: Machine tools – Safety – Turning machines

Common to all these standards is that measures against the occurrence of accidental and systematic errors are required for the development and application of functional safety components. In addition, measures must be provided to control the consequences of the occurrence of errors.

The measures to be applied in individual cases depend on the risk reduction aimed at in each case and the technology used. Details are given in the relevant basic standards such as ISO 13849-1, IEC 61508-1, IEC 62061 or IEC 61131.

In addition, there are application-specific requirements for safety devices and their use, as formulated in DIN EN 81, DIN EN 201, DIN EN 692/DIN EN 693, DIN EN 746-1/DIN EN 746-2, DIN EN 50156-1 or IEC 61511. These reflect application-specific particularities. Further explanations and descriptions are presented and additionally explained in **Annex A**. ISO 12100 is the starting point for risk assessment and derives requirements for functional safety, among other things.

The current safety-related concepts (especially regarding safety), as well as the methods for safety verification, have so far been based centrally on the assumption of a deterministic, predictable system behaviour [97]. Until now, this deterministic behaviour could be assumed if defined plants are used as a basis in the construction and design phase, in which variable but previously clearly defined processes take place. Today's safety standards assume that a system is completely developed and configured before its safety acceptance and approval (see DIN EN 61508-3/VDE 0803-3:2011-02). According to that standard no safety-relevant modifications (including repairs) may be carried out without a renewed safety-related inspection and acceptance of at least the affected subsystems [98].

The current state of safety technology follows the deterministic sensor-logic-actuator principle. However, it is to be expected that, in the strongest form of Industrie 4.0, algorithms from the field of machine learning will also be used in future for operational functions in mechanical and plant engineering in order to link production processes flexibly and intelligently [99].

In the future, in the context of Industrie 4.0, adaptable production systems through order-related recombination of production modules will be discussed. The adaptability of a system describes its ability and potential to be redesigned at will with minimal effort [95]. This adaptability is achieved by recombining, networking and automatically configuring individual production modules into production islands for specific orders. Individual modules (Industrie 4.0-components, see Chapter 2.3) are networked with each other flexibly and mostly radio-based.

This results in systems consisting of (sub)systems during the runtime of the system, which leads to a fundamental increase in the combinatorial complexity of the overall system. The structure and the overall behaviour, as well as the interdependencies of the system components cannot or can only with difficulty be predicted at the development time of the individual systems. These characteristics lead to uncertainties in the statement about the expected overall system behaviour. As a result, the methods commonly used today for the analysis and assessment of safety risks and functional safety reach their limits, since such dynamic systems and scenarios are not covered by the current safety standards or are explicitly excluded from their scope [96].

This means that the Industrie 4.0 application scenarios discussed among experts cannot be validated with today's methods for analyzing and evaluating safety, or can only be validated with considerable limitations with regard to the dynamics, variability, changeability and learning ability of the machines or process engineering plants permitted at runtime. There is therefore a need to adapt or further develop current safety engineering methods to the new or changed requirements of versatile production plants [see Figure 28 and RE 3.5-1].

As an example, the effects of Industrie 4.0 use cases on classical security architecture are shown. The dynamic configuration of systems in a production hall, i.e. the physical selection and arrangement of machines, could have effects on, for example

- escape routes in a plant or effects on fire protection concepts,
- changes in safety distances between plant parts, equipment and building parts or people in the production area,
- impacts on explosion protection through the selection and location of insufficiently qualified parts or processes,
- changes in hazards due to the incorrect combination of workpieces and manufacturing processes, or chemicals and processes,
- improper use of machine or plant components or safety devices.

It is therefore necessary that Industrie 4.0 use cases, in relation to their implementation in a plant, are evaluated using risk management methods (such as HAZOP or risk analysis according to IEC/ISO 12100). Especially the challenges of higher complexity, networking and faster configuration adjustments require new approaches to risk management and information provision over the complete life cycle of systems.

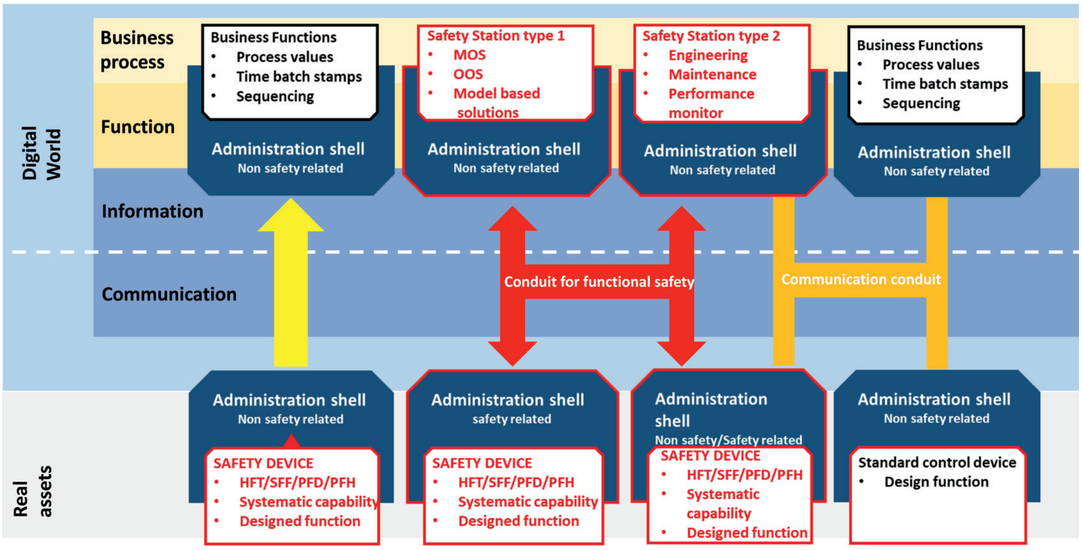


Figure 28: Functional safety requirements of versatile production plants

The interaction between the definitions of the Industrie 4.0-environment (see **Figure 28**), especially the administration shell, and the consideration of functional safety was discussed within the framework of the Industrie 4.0-cooperation between China and Germany. With the "SINO-German Whitepaper on Safety for Industrie 4.0 and Intelligent Manufacturing", an approach was presented which makes it possible to understand and apply the perspective of both areas. The white paper proposes to supplement the concept of the administration shell with the property "functionally safe"/"not functionally safe". Depending on the design of this administration shell (functionally safe/not safe), it is possible to distribute safety functions together with the associated engineering and monitoring functions within an Industrie 4.0-workspace and thus be able to react flexibly to necessary adjustments. Thus, aspects of the functional safety property of semantic interoperability can be modelled and considered throughout the entire life cycle [see **RE 3.5-2**].

As already described, versatile production systems through order-related recombination of production modules are discussed in the context of Industrie 4.0. Therefore, questions concerning the attack and manipulation security of the information and network technology used, as well as the possible influences of new technologies (such as AI) have already been focussed on. Both aspects can, however, have repercussions on safety as a whole and it is necessary to further develop procedures for a targeted and efficient consideration.

A first draft of a common application of standards on functional safety and information security was presented by the IEC in Technical Report TR 63069 [see **RE 3.5-4**]. The strategy outlined in this report describes a procedure whose goal is to create a "security environment" by means of information security measures derived from the risk analysis, which makes it possible to operate a production plant, including its safety equipment, in a sufficiently secure manner. Technical requirements are described in this context in IEC 62443**.**

3.5.2 Recommendations for action and application

3.5-1 The implementation of the Industrie 4.0-concepts leads to a further modularization of plants and components with great effects also on the engineering process. It should be considered how Industrie 4.0-concepts can also take into account plant safety and functional safety issues. This can be done by extending the concept of the administration shell to a "safe administration shell".

3.5-2 Standardized procedures and methods should be developed to enable on-time risk management throughout the life cycle without compromising the confidentiality of the technical documentation. In accordance with the most recent German-Chinese agreements, a guideline should first be developed (Sino-German Whitepaper on Functional Safety in I 4.0), which sensitizes the stakeholders with regard to the possible repercussions (risk increases or compromise of risk-reducing measures) of different Industrie 4.0 application scenarios on plant safety.

3.5-3 The effects of the use of AI systems in an industrial environment on plant safety should be considered. Current findings of AI research and application, e.g. explainable AI, should be considered as to what extent safety requirements can be met when using AI and how these requirements can be described in standards.

3.5-4 The work on safety and security should be further deepened and made more concrete. This should be done as part of the revision of IEC TR 63069. A further development towards publication as a Technical Specification (TS) or an International Standard (IS) should be discussed.

4 Artificial intelligence in industrial applications

4.1 Status and progress

Artificial intelligence (AI) is seen as an important key technology that is necessary to maintain Germany's economic performance. With regard to procedures and processes in the context of Industrie 4.0, AI has a high potential for value creation in the manufacturing and service industries. In the future, predefined, rigid manufacturing and value-added chains are to be transformed into flexible and changeable, dynamic production and service ecosystems. Traditional, but also newly designed production processes and adjacent processes, such as logistics processes, can be improved through AI. In this way, products, processes, services or new business models can be realized that are optimized, more adaptive, more fault-tolerant, or which have not been realizable to date – among other things due to their complexity. The decisive factor here is the high adaptability and problem-solving ability of the technical system.

In ISO/IEC 2382, artificial intelligence is described as a branch of computer science dedicated to the development of data processing systems that perform functions normally associated with human intelligence, such as logical reasoning, learning and self-improvement. From the point of view of industry, AI technologies are to be understood as "methods and processes that enable technical systems to perceive their environment, process what is perceived, solve problems independently, find new solutions, make decisions, in particular learn from experience, and thereby better solve tasks and act" (Russell and Norvig 1995).

In Germany, the topic of standardization of artificial intelligence is of major importance – not least because of the national artificial intelligence strategy of the Federal Government. For this reason, the topic of artificial intelligence is now being addressed explicitly and specifically for the first time in Version 4 of the Standardization Roadmap Industrie 4.0.

In standardization of AI in industrial applications, a distinction must be made between horizontal and vertical aspects. On the one hand, there are horizontal standards which are valid across all areas of application. These can be, for example, generally applicable standards for the quality measurement of (technical or informational) systems (see **Figure 29**). In contrast, standards exist in various application areas, such as Industrie 4.0. In these areas of application, specific standards are developed which reflect the concrete applications and specific requirements of the area of application.

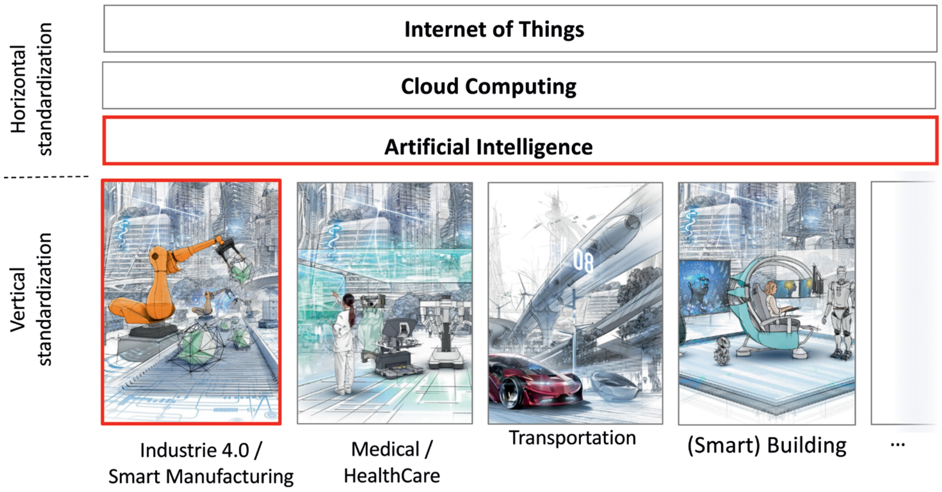


Figure 29: Relationship between horizontal and vertical standardization

4.2 Current developments

In German industry, the topic of artificial intelligence and related topics has been of major importance for several years. Within the activities of the associations VDMA, ZVEI and Bitkom, diverse working groups deal with various aspects and different applications of AI. Here, a multitude of different descriptions of the application of AI in the form of application scenarios or application examples are considered, whose interchangeability and comparability nationally and internationally is not yet given for various reasons (e.g. lack of a uniform description methodology, heterogeneous perspectives and very different levels of abstraction). [see **RE 4.1-2**].

A widespread subfield of AI is machine learning. There are currently several challenges, such as the selection of suitable data for the learning processes [see **RE 4.1-4A, RE 4.1-8A**]. Data quality, its procurement of suitable data and its integrity, security and sovereignty play a fundamental role in the use of AI. Nationally and internationally, these aspects are considered, for example, by various associations, such as the European public-private partnership Big Data Value Association, and are dealt with in the international committee ISO/IEC JTC 1/SC 42 "Artificial Intelligence". The GAIA-X project aims to create a networked data infrastructure to strengthen the European ecosystem. Standards can play a fundamental role in specifying the requirements for interoperability, data integrity, sovereignty and security and formulating their technical implementation in order to ultimately pave the way for the successful application of AI [see **RE 4.1-9**]. In this way, the interface between the regulatory framework of a GAIA-X ecosystem and standards developed privately within the European legal framework can be defined.

Although the project work on the GAIA-X ecosystem is still ongoing, fields of action are already emerging. At the beginning of 2019, an inter-group AI project group was initiated under the leadership of Working Group 2 "Technology and Application Scenarios" (AG2) of the Platform Industrie 4.0. The project group is dealing with the general processing and positioning of the topic "artificial intelligence" in the context of Industrie 4.0 on the basis of application scenarios. The defined application scenarios of the Platform Industrie 4.0

and their further development within the framework of the work of AG 2 and the AI project group of the Platform Industrie 4.0 represent a starting point for deriving concrete recommendations for action, standardization and needs for standardization. A further refinement of both the (technology-independent) application scenarios and the application examples with concrete technology reference is necessary [see RE 4.1-2].

Within the framework of the activities of the AI project group of the Platform Industrie 4.0, the need for a general location framework for artificial intelligence technologies and methods suitable for Industrie 4.0 was also identified. The location framework is intended to be (technology-neutral) the impact of the application of artificial intelligence, as well as a framework for putting possible technologies to be used (such as the periodic table AI developed by BITKOM) into context, for example an increasingly possible autonomy in the form of autonomy classes [see RE 4.1-3, RE 4.1-4A].

The use of AI in industrial applications can, depending on the application purpose and function of the AI, influence the fulfilment of requirements described in standards. For example, if AI technology is used to adapt the behaviour of automated functions, the influence of the AI's actions on the automated system must be considered in the conformity assessment. This also applies in particular to industrial applications with functional safety requirements. Consequently, it is necessary to always check and ensure the fulfilment of normative framework conditions, especially considering the function and influence of AI [see RE 4.1-4A]. An objective assessment of the AI's sphere of influence is particularly necessary in this context [see RE 4.1-3].

The currently high interest in AI leads to a multitude of different activities within different associations, institutions, consortia and societies regarding the application and standardization of AI. The Standardization Council Industrie 4.0 (SCI 4.0) established the Expert Council for Artificial Intelligence in Industrial Applications in order to avoid parallel additional work in the standardization of AI for industrial applications, to promote the exchange between these different activities, and, ultimately, to develop a national opinion that is as harmonized as possible. The objective: national coordination and harmonization of standardization activities to develop a consolidated picture of requirements and standardization needs in the context of AI in Industrie 4.0 of the German economy, and coordination of appropriate standardization activities (see Figure 30).

The Expert Council for Artificial Intelligence in Industrial Applications plays an essential role and is the centre for discussions on standardization and coordination in the field of artificial intelligence for industrial applications. The tasks include the collection of use cases [see RE 4.1-2] and the derivation of standardization requirements based on them, the development and specification of recommendations for action and their incorporation in various national and international standardization roadmaps currently being developed and those to be developed in the future, and the coordination of national and international standardization activities [see RE 4.1-1, RE 4.1-7].

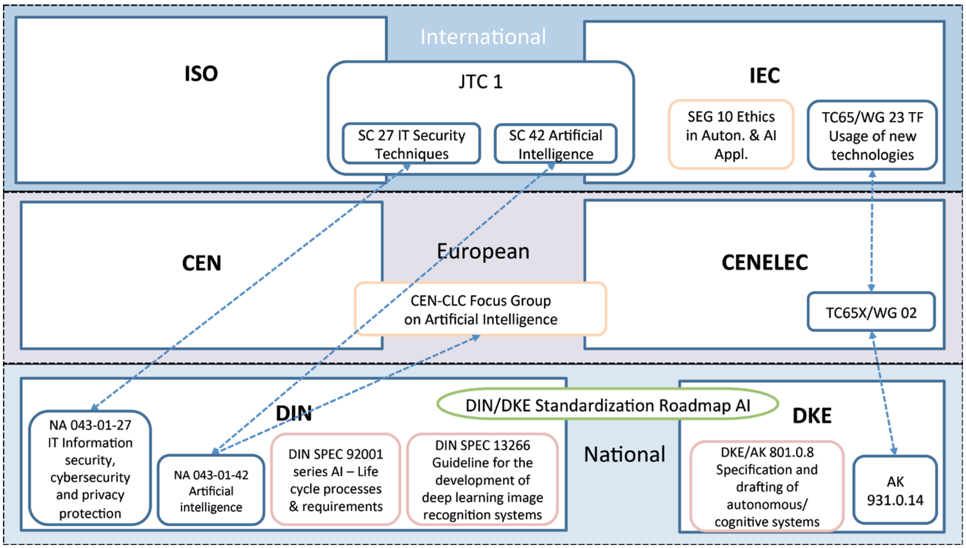


Figure 30: Overview of national and international standards bodies working on AI for Industrie 4.0

In order to appropriately address the objectives of the AI strategy of the Federal Government in the context of standardization, two standardization roadmaps were initiated, which provide detailed and ongoing information on the various aspects of AI. In November 2018 a project was initiated to identify ethical aspects in standardization for AI in autonomous machines and vehicles. The project is intended to provide an overview of how ethical rules can be incorporated into the standardization of requirements for technology, processes and services. The results of this project will be included in the DIN/DKE Standardization Roadmap Artificial Intelligence, a first version of which is to be published in autumn 2020.

The Standardization Roadmap Artificial Intelligence is primarily intended to address the following seven topics: Foundations (data, terminology, classification, AI elements), ethics/responsible AI, quality and certification, IT security in AI systems, industrial automation, mobility and logistics, AI in medicine. The available results will then be further processed and integrated into the Standardization Roadmap Artificial Intelligence.

Currently, some horizontal aspects are already being developed nationally in the form of DIN SPEC specifications; these and the interrelationships of the committees described below are shown in **Figure 30**. The DIN SPEC 92001 series deals with the life cycle and quality requirements of artificial intelligence. Part 1 of the DIN SPEC 92001 series provides a general quality metamodel for artificial intelligence, which primarily describes the most important aspects of AI quality; Part 2 of the series focuses on the topic of robustness and presents the AI-specific quality requirements of the quality model from Part 1. DIN SPEC 13266 describes a guideline for the development of deep learning image recognition systems and was published in the second quarter of 2020. The DIN SPECs focus on general AI aspects and can subsequently be used to develop Industrie 4.0-specific standards and specifications. Within DKE/AK 801.0.8, a VDE application rule VDE-AR-E 2842-61-1 "Specification and design of autonomous/cognitive systems" is being developed, in which terms and concepts for dealing with autonomous/cognitive systems are defined. A reference model for system and application architectures will be developed that considers the entire life cycle with the aim of achieving trustworthy systems. Some approaches from the field of functional safety are transferred to this reference system, such as safety integrity level (SIL) or Lambda (probability of failure). The application rule addresses horizontal aspects, such as management requirements, the development of AI blueprints and aspects of market surveillance.

In the development and operation of components, machines and systems, compliance with requirements described in standards, such as limit values, procedures or reference values defined therein, plays a fundamental role. Currently, standards and specifications are mostly available in document form, with the aim of being read, understood and appropriately taken into account by people. As a result, machine processing and interpretation of the normative information is currently only possible to a limited extent. If information in standards is to be taken into account efficiently when using methods of artificial intelligence, it must be available in a suitable manner and prepared for machine processing. For this purpose, data structures, (exchange) formats, a formalization or mathematization of the contents as well as corresponding access possibilities must be created [see RE 4.1-8A].

It should be noted that the topic of "digital standards" is important beyond the application of AI. Industrie 4.0 can play a pioneering role in the application of digital standards; AI is a possible application that can benefit from this [see RE 4.1-8A]. In contrast to the previous approach, the perspective of standardization changes in this case: Whereas standards on AI have been considered so far, the application and evaluation of standards by AI is (also) considered in this context.

The topic of AI or related aspects is considered in various standardization bodies.

Within the ISO/IEC JTC1 joint committee, the committee SC 42 "Artificial Intelligence" was founded in April 2018. As a focus of AI standardization within ISO and IEC, the work of SC 42 considers the entire AI ecosystem. In addition, the work of SC 42 is intended as an orientation guide for ISO and IEC committees that develop artificial intelligence applications. The current portfolio of the committee includes standardization in the areas of AI terminology and concepts, machine learning, big data, AI trustworthiness (e.g. security, safety, privacy, robustness, resiliency, reliability, transparency, controllability), applications and use cases of AI, governance implications of AI, computational approaches of AI, ethical and societal concerns, risk management, data quality in relation to AI and quality requirements. (see Figure 30).

The motivation for the development of such standards is to provide a high-level description of the area and its various components, and to provide a basic understanding and common language for a variety of stakeholders.

ISO/IEC JTC 1/SC 27 deals with the topics of information security, cyber security and privacy protection. Two studies are currently being prepared in this context: A study on the impact of AI on privacy and another study on trustworthiness.

IEC/SEG 10 deals with ethical aspects in autonomous applications and AI as an important approach to technology acceptance. In particular, socially relevant aspects are being considered and recommendations to the IEC Standardization Management Board (SMB) are being developed.

The Task Force "Usage of new technologies" of IEC/TC 65/WG 23 is carrying out an evaluation of new technologies and their relevance for standardization in the field of "smart manufacturing". Here artificial intelligence in industrial applications is being regarded as a future technology. Work in this vertical AI area is mirrored at national level in working group DKE/AK 931.0.14.

Work at European level is also presented in Figure 30. The Focus Group on Artificial Intelligence was established at CEN-CENELEC in April 2019. The focus group advises CEN and CENELEC on the development and dissemination of AI in Europe. The group's work will focus on ways to respond to specific European needs, while generally global issues will be addressed at the global level, where possible. Among other things, the focus group will take into account the guidelines of the High Level Expert Group on Artificial Intelligence set up by the European Commission and COM (2018) 237 on Artificial Intelligence for Europe. The focus group is developing a common vision for European AI standardization. Within CENELEC Technical Committee CLC/TC 65X, aspects of the use of AI in industrial automation are considered at European level.

The national mirror committee of ISO/IEC JTC 1/SC 42 "Artificial Intelligence" and the CEN CENELEC Focus Group on AI is the Working Group "Artificial Intelligence" (NA 043-01-42 AA) within DIN's Standards Committee Information Technology and Selected IT Applications. Industrie 4.0 is seen here – as is usual in horizontal standardization – as one of many application areas whose requirements are covered by use cases. The SCI 4.0 Expert Council AI for industrial applications was established as a link between this horizontal body and the committees for industrial applications – especially IEC/TC 65 [see RE 4.1-7].

An overview of ongoing activities in the field of AI standardization and standardization at European and international level is being developed as part of the Stand.ICT.eu consortium project funded by the EU under Horizon 2020. An updated version of the document is in preparation. [see RE 4.1-6, RE 4.1-7].

4.3 Recommendations for action and application

Standardization of AI-relevant technologies should aim at a balanced differentiation between horizontal issues (e.g. terminology) and sector-specific needs.

4.1-1 Standardized terminology of artificial intelligence for Industrie 4.0
Definitions of terms in existing (international) standards with a focus on "artificial intelligence" are to be continuously checked for consistency with regard to their applicability in Industrie 4.0 and clarified where necessary. Identified inconsistencies and obstacles to application are to be dealt with in the corresponding standards committees.

4.1-2 Application scenarios and application examples
Based on the preliminary work of Working Group 2 of the Platform Industrie 4.0, nationally coordinated application scenarios and application examples for artificial intelligence in Industrie 4.0 are to be developed and introduced into bilateral and international working and expert groups, as well as standards committees. The use of a uniform template and application of the IIRA Viewpoints should be aimed at.

4.1-3 Standardized assessment framework for the application of AI methods
A uniform location and assessment framework for AI methods should be developed by horizontal standardization bodies. Appropriate classifications of the autonomy of technical systems, necessary metrics for evaluation methods for Industrie 4.0, as well as further requirements, concepts and methodologies should be addressed by vertical standards committees and should be introduced in standards committees in an appropriate manner.

4.1-4A Checking the extent to which AI methods meet the requirements for functions as described in existing standards
Before using artificial intelligence in industrial applications, it must be checked whether the requirements of relevant standards can be met.

4.1-5 Trustworthiness of AI
The importance of trustworthiness of artificial intelligence or systems in which AI processes, technologies or methods are used shall be investigated in detail (see also RE 4.1-1, RE 4.1-2), in particular, the fundamental reference to cross-sectional technologies such as IT security and functional safety are to be considered.

4.1-6 Development and continuous updating of a standardization map and derivation of strategies for action
In order to take advantage of the various recommendations for action described in the Standardization Roadmap for AI (see in particular RE 4.1-1, RE 4.1-2, RE 4.1-4A, RE 4.1-5), the development and continuous updating of a standardization map for artificial intelligence in general, and for AI in industrial applications in particular, is recommended. In particular, the exchange with other international standardization activities of ISO, IEC and at European level (e.g. the Stand.ICT.eu project or the Artificial Intelligence focus group) should be actively promoted (see also RE 4.1-7).

4.1-7 Synchronization, coordination and exchange with (national and international) standardization roadmaps and guidelines
The cross-committee exchange between standardization activities in the context of artificial intelligence, the safeguarding and ensuring of the requirements of industrial automation in horizontal standardization committees, and the coordination and harmonization of requirements and standardization activities of artificial intelligence for Industrie 4.0 in the sense of vertical standardization must be strengthened. In particular, the exchange between horizontal standards bodies (such as ISO/IEC JTC/1 SC/42) and vertical needs and requirements in Industrie 4.0 is necessary and can only be ensured by the participation of industrial representatives in these bodies and national, institutional representatives of vertical and horizontal standards organizations. This task should be entrusted to a body for the coordination and harmonization of standardization activities in the context of Industrie 4.0, which works in close coordination with horizontal standardization bodies and explicitly addresses the topic of artificial intelligence.

4.1-8A Digitally formulated standards and specifications for automated evaluation

Industrie 4.0, and especially the use of AI, can play a pioneering role in the application of digitally formulated standards and specifications. This requires both the availability of digitally formulated standards and suitable evaluation procedures. The application of digitally formulated standards for automated evaluation should be investigated and promoted. For example, machine-interpretable standards can be used for automatic evaluation in the development of components, machines and systems in order to automatically check the conformity of developments to standards (see RE 4.1-4A).

4.1-9 Standardization to ensure data sovereignty, integrity and security

The application of standardization for the management, storage, exchange and use of suitable data and for ensuring data sovereignty, data integrity and data security should be investigated and promoted in order to ensure the need for suitable, integrated data for automatic learning processes in the context of AI.

Annex A Further information on functional safety

Table 2: The basic procedure underlying all current relevant standards for the design of safety devices is as follows:
1. A risk analysis is carried out in which the expected risk of a device is estimated.
2. Safety functions are assigned to the identified risks.
3. Risk reduction factors are assigned to the safety functions.
4. The technical design of the safety functions is specified.
5. The safety function is implemented.
6. The safety function is commissioned.
7. The safety function is operated.
8. The safety function is modified.
9. The safety function is decommissioned.
10. The safety function is disposed of.
This sequence of activities is referred to as the safety life cycle.

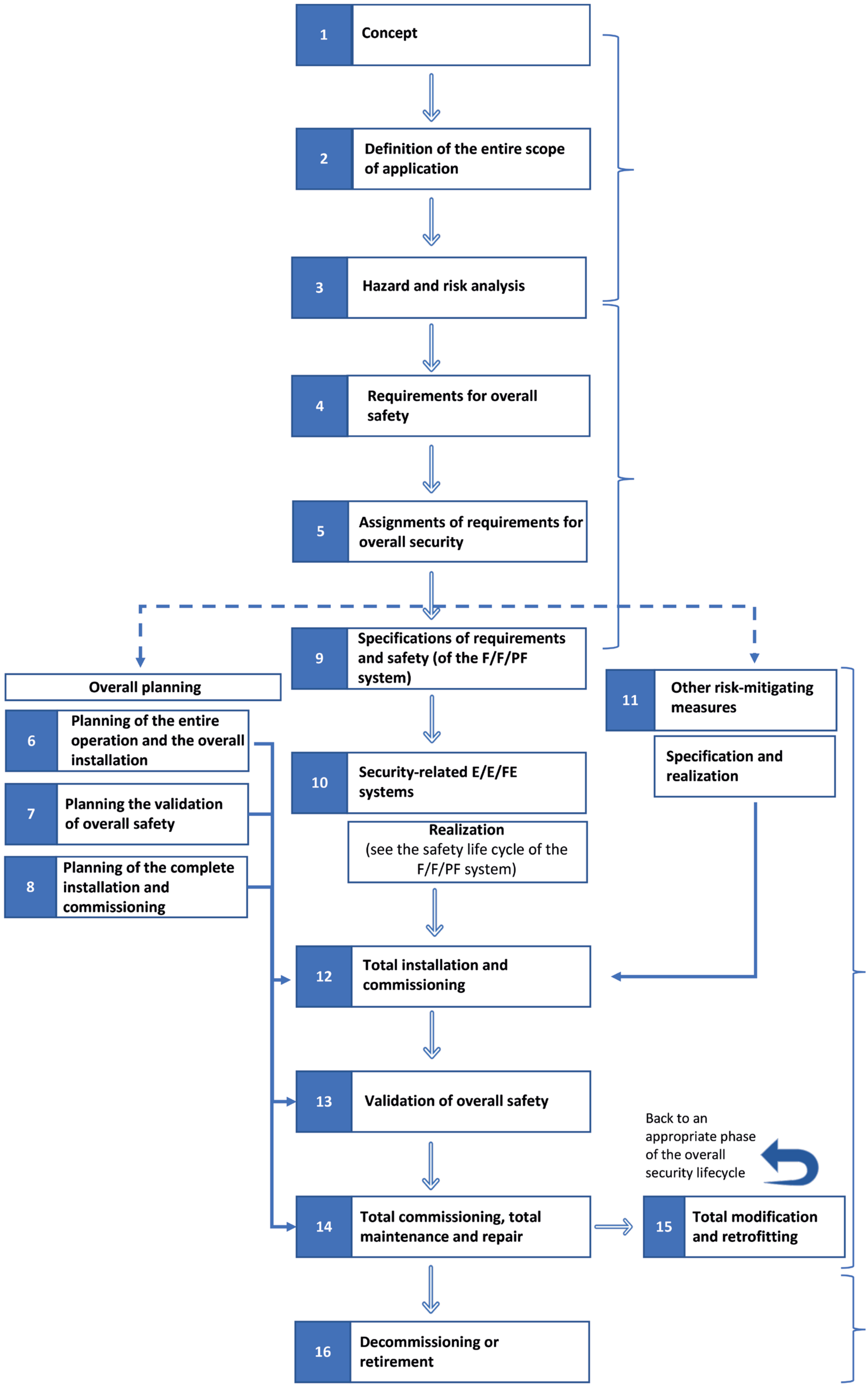


Figure 31: Safety life cycle as in IEC 61508-1

A risk analysis is carried out in Step 1 of the life cycle. An example is the process on which ISO 12100 is based.

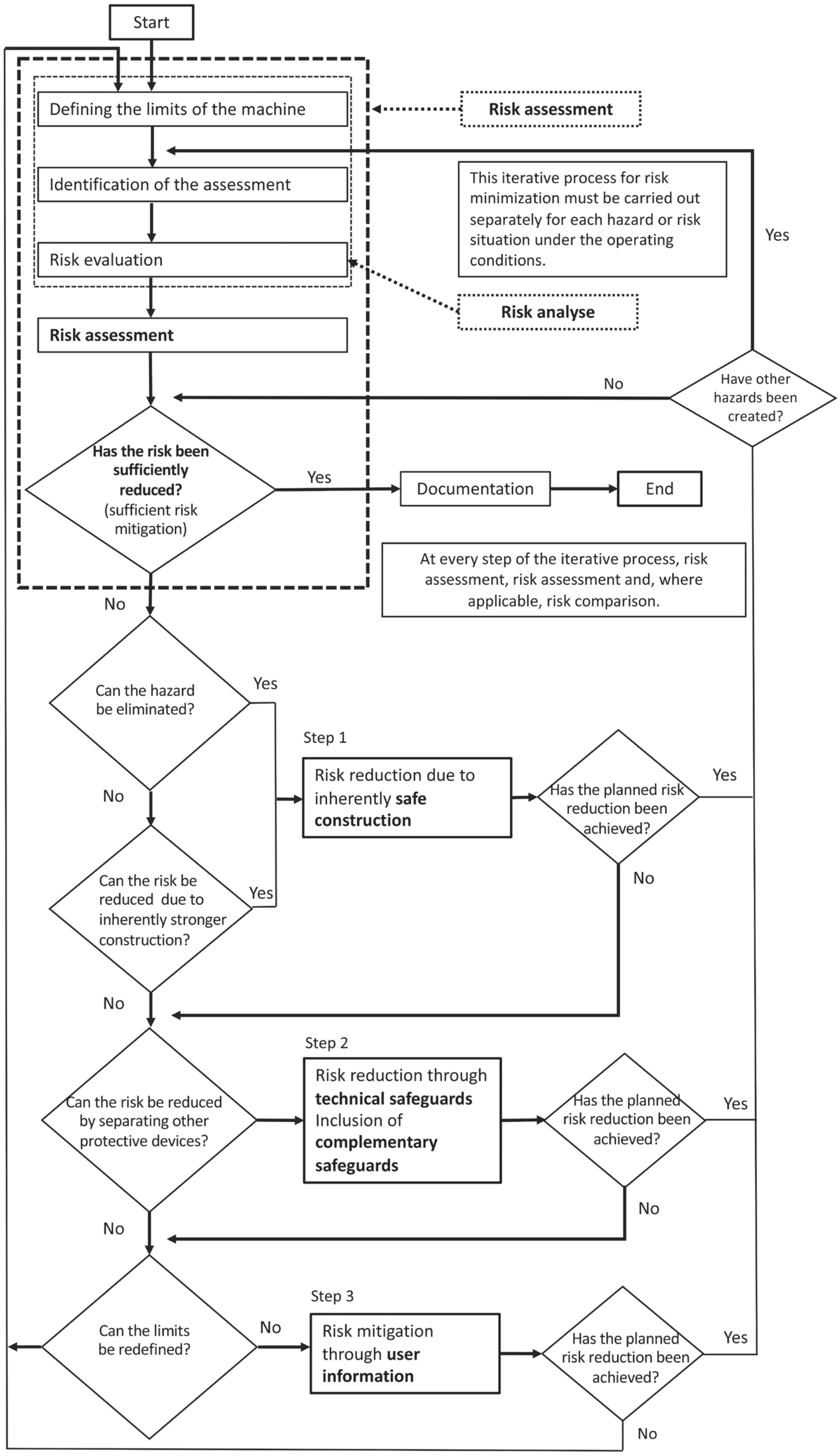


Figure 32: Definition of the necessary risk reduction according to ISO 12100

If technical risk reductions are required according to such a process (in addition to the ones described above, there are a number of alternatives), there are various ways of formulating the necessary technical requirements.
Qualitative methods are often used:

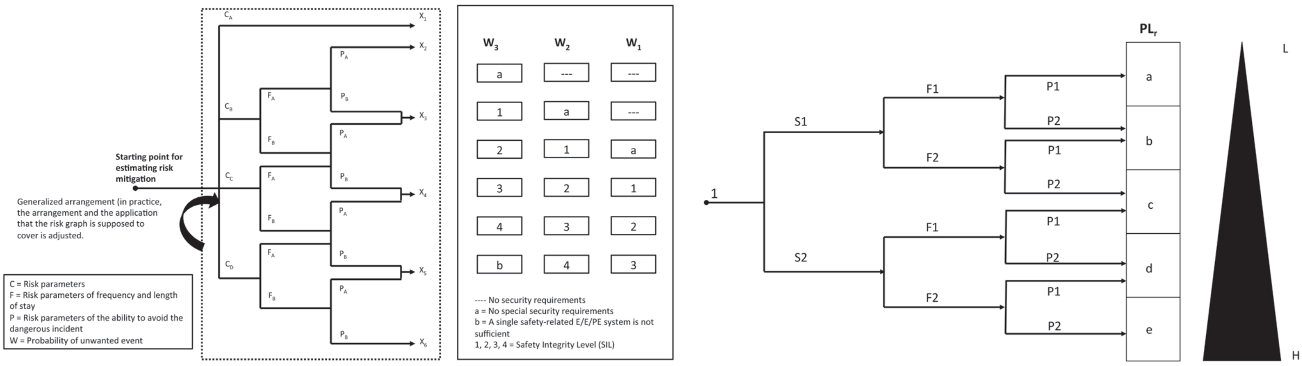


Figure 33: Implementation of risk reduction as in IEC61508/ISO13849

When using these methods, it is important to calibrate the decision parameters accordingly. When life cycle steps 2 to 6 are completed, an assessment is required in each case to demonstrate that the requirements defined in the previous step have been met. In steps 5 and 6 additional functional tests are carried out. In step 7 of the life cycle, regular checks of the correct functionality of a safety device are carried out. In step 8 of the life cycle it is necessary to establish a decision process besides the technical change procedure, which allows the identification of the life cycle phases to be considered in case of a change. In steps 9 and 10, it must be ensured that the effectiveness of a safety device is adequately maintained until the source of risk has been completely removed.

In order to formulate the requirements resulting from these considerations for the development of components for safety functions in an application-neutral manner, generic requirement levels were formulated in the relevant basic standards (ISO 13849 and IEC 61508), which result in the following specifications

Table 3: Overview of normative requirements

<table>
<tr><th colspan="3">ISO 13849</th><th colspan="3">IEC 61508
(High/continuous requirement)</th><th colspan="3">IEC 61508
low requirement</th></tr>
<tr><th>Demand</th><th colspan="2">Required admissibility</th><th>Demand</th><th colspan="2">Required admissibility</th><th>Demand</th><th colspan="2">Required admissibility</th></tr>
<tr><th>PL</th><th>Lower border</th><th>Upper limit</th><th>SIL</th><th>Lower border</th><th>Upper limit</th><th>SIL</th><th>Lower border</th><th>Upper limit</th></tr>
<tr><td>a</td><td>1,00E-04</td><td>1,00E-05</td><td>-</td><td></td><td></td><td>-</td><td></td><td></td></tr>
<tr><td>b</td><td>1,00E-05</td><td>3,00E-06</td><td>1</td><td rowspan="2">1,00E-05</td><td rowspan="2">1,00E-06</td><td>1</td><td rowspan="2">1,00E-01</td><td rowspan="2">1,00E-02</td></tr>
<tr><td>c</td><td>3,00E-06</td><td>1,00E-06</td><td>1</td><td>1</td></tr>
<tr><td>d</td><td>1,00E-06</td><td>1,00E-07</td><td>2</td><td>1,00E-06</td><td>1,00E-07</td><td>2</td><td>1,00E-02</td><td>1,00E-03</td></tr>
<tr><td>e</td><td>1,00E-07</td><td>1,00E-08</td><td>3</td><td>1,00E-07</td><td>1,00E-08</td><td>3</td><td>1,00E-03</td><td>1,00E-04</td></tr>
<tr><td colspan="3"></td><td>4</td><td>1,00E-08</td><td>1,00E-09</td><td>4</td><td>1,00E-04</td><td>1,00E-05</td></tr>
</table>

When comparing the technical requirements of the two standards, the following aspects should primarily be considered:

The structuring of the requirements according to ISO 13849 (Performance Level PL) and IEC 61508 (Safety Integrity Level SIL) differ in that when the PL was defined, the specifications were spread out (PL b and c), which focuses on the area of frequent applications, while IEC 61508 provides a linear division of the considered risk reduction.

IEC 61508 distinguishes two operating modes of safety devices. This takes into account the fact that there are application areas in which it is assumed that the respective safety function is not activated during normal operation. This consideration results in error models that have to be considered differently, as well as other requirement parameters (error per requirement vs. error per operating hour).

The basic standards formulate requirements for the design, development and manufacture of components for safety functions.
These requirements include measures to avoid errors, identify errors, and control errors in order to meet the generic requirements shown in Table 3.

Both random and systematic errors must be considered. In addition, both hardware and software errors, as well as external influences such as failure of the auxiliary power supply must be considered. The above requirements refer to both individual components and application-specific combinations of devices.

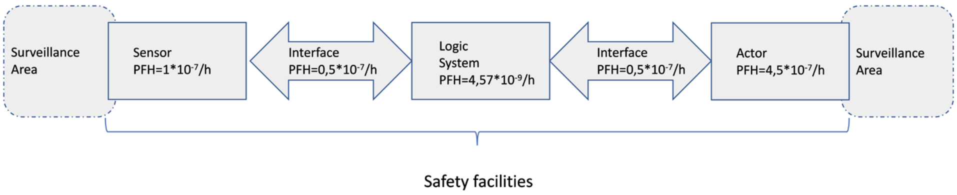


Figure 34: Delimiting a safety device

The device to be considered in **Figure 34** extrends from the connection of the sensors with the monitoring area to the connection of the actuators to the risk source. Since the starting parameter is the required risk reduction of the overall arrangement, there is a need to consider all components both individually and in combination. In a simple configuration, the reliability of the overall arrangement can be achieved by adding the reliability of the individual components. Besides the components involved, the interfaces must also be considered.

In addition, any existing diagnostic functions must be considered, which is why all interfaces are shown as bi-directional functions in **Figure 28**. Depending on the application, in addition to the reliability of the overall arrangement with regard to random errors occurring according to a statistical pattern, the consideration of systematic error sources, such as wear, but also the influence of the media to be monitored (e.g. due to corrosion) must be considered.

Besides the hardware errors described above, software errors must also be considered. It must be taken into account that software errors are basically of a systematic nature, i.e. they are present in software – or not. This consideration results in the requirement for appropriate software development processes, which are sufficiently backed up with checks and functional tests.

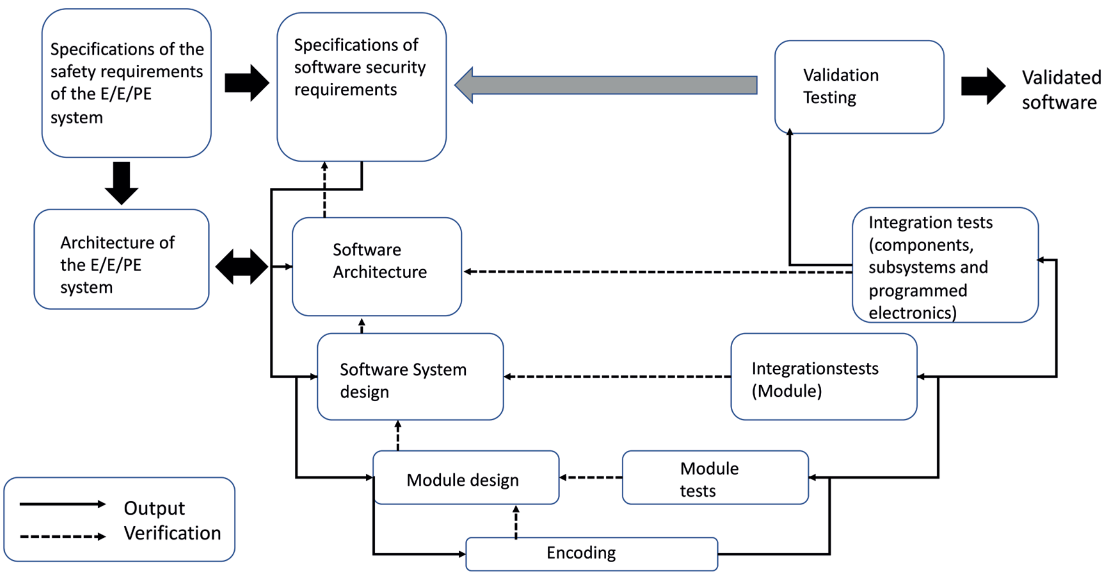


Figure 35: Software development process according to IEC 61508-1 shows the software development process specified by IEC 61508-3.

For the design of the individual activities, IEC 61508-3 contains proposals for the definition of individual bundles of measures to ensure a sufficient level of quality for the software to be created.

Annex B Overview of the I 4.0 standardization environment

For an overview of current standards relevant to Industrie 4.0 go to
www.din.de/go/industrie 4-0
www.dke.de/Normen-Industrie40

B.1 German standardization bodies in the Industrie 4.0 context

DKE	
DKE/GK 914	Functional safety of electric, electronic and programmable electronic systems (E, E, PES) for protection of persons and the environment
DKE/AK 914.0.4	Updating IEC 61508-2
DKE/AK 914.0.6	Cooperation ITEI/Reliability
DKE/K 931	System aspects of automation
DKE/AK 931.0.12	Life Cycle Management
DKE/AK 931.0.14	Smart manufacturing and Industrie 4.0
DKE/UK 931.1	IT security for industrial automation systems
DKE/AK 931.1.3	Functional security – IT security
DKE/K 941	Engineering
DKE/AK 941.0.2	Automation ML
DKE/K 956	Industrial communication
DKE/AK 956.0.2	Industrial Wireless Networks
DKE/AK 956.0.6	Cooperation ITEI/Radio
DIN	
DIN Standards Committee Information Technology and Selected Applications (NIA)	The scope of the DIN Standards Committee for Information Technology and Selected Applications (NIA) comprises the development of standards in the field of information technology and selected fields of application of information. Its Annual Reports are found at its dedicated website.
NA 043-01 FB	Special Division Basic Standards of Information Technology
NA 043-02 FB	Special Division Horizontal Application Standards of Information Technology
NA 043-01-27 AA	Information security, cybersecurity and privacy protection
NA 043-01-41 AA	Internet of Things
NA 043-01-42 AA	Artificial Intelligence
DIN NA 060 NA 060-30 FB	Standards Committee Mechanical Engineering Section Automation systems and integration
VDI/VDE Gesellschaft Mess- und Automatisierungstechnik (VDI/VDE Society for Measurement and Automatic Control)	
VDMA	
Companion Specifications	

B.2 European and international standardization organizations

IEC – International Electrotechnical Commission	
IEC/TC 65	Industrial-process, measurement, control and automation
IEC/TC 65/WG 10	Security for industrial process measurement and control – Network and system security
IEC/TC 65/WG 16	Digital Factory
IEC/TC 65/WG 19	Life-cycle management for systems and products used in industrial-process measurement, control and automation
IEC/TC 65/WG 20	Industrial-process measurement, control and automation– Framework to bridge the requirements for safety and security
IEC/TC/WG 23	Smart Manufacturing Framework and System Architecture
IEC/TC/WG 24	Asset Administration Shell for Industrial Applications
IEC/SC65	Industrial-process measurement, control and automation
IEC/SC 65A	System Aspects
IEC/SC 65B	Measurement and control devices
IEC/SC 65C	Industrial Networks
IEC/SC 65E	Devices and integration in Enterprise systems
ISO/IEC	
Joint ISO/TC 184 – IEC/TC 65/JWG 21	Smart Manufacturing Reference Model(s)
ISO/IEC JTC 1	**Joint Technical Committee for Information Technologies**
ISO/IEC JTC 1/SC 27	Information security, cybersecurity and privacy protection
JTC 1/SC 27/WG 3	Security evaluation, testing and specification
JTC 1/SC 27/WG 4	Security controls and services
JTC 1/SC 31	Automatic identification and data capture techniques
ISO/IEC JTC1/SC 41	Internet of Things and Related Technologies
ISO/IEC JTC1/SC 42	Artificial Intelligence
ISO/IEC JTC 1/AG 7	Trustworthiness
ISO/IEC JTC 1/AG 8	Meta Reference Architecture and Reference Architecture for Systems Integration
ISO/IEC JTC 1/AG 11	Digital Twin
ISO – International Organization for Standardization	
ISO/TC 184	Automation systems and integration
ISO/TC 184/SC 4	Industrial data
ISO/TC 108 SC 5	Condition monitoring and diagnostics of machine systems
ISO/TC 261	Additive Manufacturing
ISO/TC 292	Security and resilience

ISO/TC 299	Robotics
ISO/TC 307	Blockchain und Technologien für verteilte elektronische Journale
CEN – European Committee for Standardization	
CEN/TC 114	Machinery Safety
CEN/TC 310	Advanced Automation technologies and their applications
CEN/TC 319	Maintenance
CEN/TC 438	Additive Manufacturing
CENELEC – European Committee for Electrotechnical Standardization	
CLC/TC 65X	Industrial-process measurement, control and automation
CLC/TC 65X WG 02	Smart Manufacturing
IEEE – Institute of Electrical and Electronics Engineers	
IEEE 802	Time sensitive networks
IEEE P2806	System Architecture of Digital Representation for Physical Objects in Factory Environments
DR_WG	Digital Representation Working Group
ETSI	
3GPP	3rd Generation Partnership Project
ESI	Electronic Signature
ISG SAI	Securing AI
Cyber	Cybersecurity
ISG MEC	Multi-access Edge Computing
oneM2M	
SmartM2M & SAREf	Smart App Reference Ontology
ITU-T	
FG-5GML	Machine Learning for Future Networks including 5G (Focus Group)
IECEE	
IECEE CMC WG 31	Cyber Security Certifications
IECEE OD 2061	Industrial Cyber Security Program Specifies 7 Cyber Security Certifications based on IEC 62443
IECEE OD 2037	ch. 12/Annex 5: Industrial Cyber Security Certificate Structure
IECEE Test Report Forms (TRFs)	TRFs for IEC 62443 parts 2-4, 3-3, 4-1 and 4-2

B.3 Coordinating bodies

CEN-CENELEC ETSI	
CEN-CLC-ETSI/SMa-CG Coordination Group on Smart Manufacturing	The CEN-CENELEC-ETSI "Coordination Group on Smart Manufacturing" (SMa-CG) was founded in 2019 and is managed by DIN/DKE. The Coordination Group advises on current European activities related to Smart Manufacturing and synchronizes the position of CEN, CENELEC and ETSI vis-à-vis SDOs and other third parties on standardization. Germany holds the secretariat of the Group.
ISO	
ISO/TMBG/SMCC **Smart Manufacturing Coordinating Committee (SMCC)**	Also under German leadership, the ISO/SMCC "Smart Manufacturing Coordinating Committee" has since then been actively promoting international work on the topic of Industrie 4.0. The aim here is to coordinate the topic across the board and to develop recommendations for implementation, particularly with regard to a joint international approach. At the same time, a national mirror committee was set up at DIN in order to offer interested parties a national platform to play a decisive role in shaping international work.
IEC	
IEC/SyC System Committee Smart Manufacturing	The IEC/SyC "System Committee Smart Manufacturing", which is chaired by Germany, is directly answerable to the Standardization Management Board (SMB) of IEC and started its work in 2018. The tasks of the IEC/SyC are, in addition to the coordination of standardization activities, the identification of gaps and overlaps, especially in the cooperation of relevant standards organizations and consortia-Das unter deutschem Vorsitz stehende Gremium.
IEC/SyC Communication Technologies and Architectures	In mid-2019, the IEC/SyC "Communication Technologies and Architectures", which emerged from the previous IEC/SEG 7, was also created. The tasks of the SyC are standardization in the field of communication technologies and architectures. The SyC aims to coordinate and harmonize activities in the field of communication technologies and architectures. The committee works closely with the IEC committees to support their ongoing work in the field of communication technologies. Another objective is to cooperate with other standards development organizations (SDOs) and industry consortia in the field of communication technologies.

B.4 Industrie 4.0 initiatives

Standardization Council Industrie 4.0
www.sci40.de

Plattform Industrie 4.0
www.plattform-i40.de/
Working Group 1: Reference architectures, standards and specifications
Working Group 2: Technology and application scenarios
Working Group 4: Legal Framework
Working Group 3: Security of networked systems
Working Group 5: Work and training
Working Group 6: Digital Business Models in Industrie 4.0

Labs Network Industrie 4.0
www.lni40.de

GAIA – X
www.data-infrastructure.eu

iDIS – Initiative Digitale Standards

5G ACIA **–** Alliance for Connected Industries and Automation

B.5 Standards Setting Organizations (SSO)

OPC – Unified Architecture	
Standard for data exchange as a platform-independent, service-oriented architecture	
AutomationML	
Open standard for neutral, XML-based data format for the storage and exchange of plant design data	
ecl@ss	
Data standard for the classification and unambiguous description of products and services using standardized ISO-compliant properties	
NAMUR	
Working group 2.8: "Automation networks and services" (Namur Open Architecture NOA)	
W3C (see **Chapter 2.5.2**)	
W3C WoT resources	W3C WoT Wiki
	W3C WoT Interest Group
	W3C WoT Working Group
WebRTC	Deals with the basic real-time capability between things, based on a corresponding WoT standard, formal description. WebRTC is standardized by the World Wide Web Consortium (W3C) as an open standard.
WebAssembly	A new objective as a replacement for Java Script in the browser, combined with developments to make it available outside of browsers (Spinoff:) and thus to bring performance for browser-based applications into the performance domain of classic web applications.
WebPerf	Performance: the ability to react agilely to different requirements and to implement this high performance in a uniform integration
WebPayments	Introduce integration of payment traffic systems between things, whereby these can also act autonomously. Ask about standards (PSD2, EU, EMV intl. WeChat. Tencent, SCS (China)
Immersive	AR/VR integration in the web context also for things but also autarchic between things and people
Webauthn	The development of a corresponding security architecture based on standards but integrated between things, based on a corresponding integration along all model layers both horizontally and vertically (question of views)
Extensible Web	The introduction of extensibility as an integral concept for browsers, later via WASI (WebAssembly System Interface) also for non-browser-based application developments as an alternative to Java (bytecode) generation

B.6 Overview of political institutions (Germany, Europe)

BMWi – German Federal Ministry for Economic Affairs and Energy

BMBF – German Federal Ministry of Education and Research

European Commission

Multi Stakeholder Platform (MSP)
Digitising European Industry (DEI)

List of abbreviations

3GPP	3rd Generation Partnership Project
AAL	Ambient Assisted Living
acatech	German National Academy of Science and Engineering
AK_STD	*Arbeitskreis Standardisierung* (Working Group Standardization)
AAS	Asset Administration Shell
AASX	Asset Administration Shell Explorer
ADT	Abstract data type
AML	Automation Markup Language
B2B	Business-to-Business
BITKOM	*Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V.* (Federal Association for Information Technology, Telecommunications and New Media)
BMBF	*Bundesministerien für Bildung und Forschung* (Federal Ministries of Education and Research)
BMEcat	Catalog standard for your e-business
BMWi	*Bundesministerium für Wirtschaft und Energie* (Federal Ministry for Economic Affairs and Technology)
BSD	Berkeley Software Distribution
BSI	*Bundesamt für Sicherheit in der Informationstechnik (Federal Office for Information Security)*
BZKI	*Begleitforschung für zuverlässige Kommunikation in der Industrie (Accompanying Research – Reliable wireless communication in industry)*
CDD	Common Data Dictionary
CEN	*Comité Européen de Normalisation*/European Committee for Standardization
CENELEC	*Comité Européen de Normalisation Électrotechnique/* European Committee for Electrotechnical Standardization
CPPS	Cyber Physical Production System
CPS	Cyber Physical System
CVRF	Common Vulnerability Reporting Framework
DEI	Digitising European Industry
DG CONNECT	Directorate Generale CONNECT
DG GROW	Directorate General GROW
DG RTD	Directorate General Research and Innovation
DIN	*Deutsches Institut für Normung e.* V. (German Institute for Standardization)
DIN SPEC	DIN Specification
DKE	*Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE* (German Commission for Electrical, Electronic & Information Technologies of DIN and VDE)
DNS	German Standardization Strategy
EBN	R & D phase standardization
EDDL	Electronic Device Description Language
EN	*Europäische Norm* (European Standard)
EPL	Eclipse Public License
ERP	Enterprise Resource Planning
ETSI	European Telecommunications Standards Institute
EU	European Union
GDPR	General Data Protection Regulation

GL	*Grundlagen* (Fundamentals)
GMA	*VDI/VDE Gesellschaft Mess- und Automatisierungstechnik* (VDI/VDE Society for Measurement and Automatic Control)
GUI	Graphic User Interface
HAZOP	Hazard and Operability Process
HE	*Handlungsempfehlung* (Recommendation for action)
HTTP	Hypertext Transfer Protocol
IACS	Industrial Automation and Control System
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ICT	Information and communications technology
IML	Fraunhofer Institute for Material Flow and Logistics
IOSB	Fraunhofer Institute of Optronics, System Technologies and Image Exploitation
ICT	Fraunhofer Institute for Information and Communications Technologies
IoT	Internet of Things
IPA	Fraunhofer Institute for Process Automation
IIoT	Industrial Internet of Things
IPA	Fraunhofer Institute for Manufacturing Engineering and Automation
IP45G	Information platform for 5 G – Industrial Internet
ISA	International Sociological Association
ISO	International Organization for Standardization
IT	Information Technology
ITA	Industry Technical Agreement
ITG	*Informationstechnische Gesellschaft im VDE* (VDE Information Technology Society)
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union, Radiocommunication Sector
JETI	JTC1 Emerging Technology and Innovation
JIS	Joint Initiative on Standardization
JTC	Joint Technical Committee der IEC und ISO
JSON	JavaScript Object Notation
JWG	Joint Working Group
KI	Artificial Intelligence
KMU	*Klein- und Mittelständische Unternehmen* (Small- and mid-sized enterprises, SMEs)
LGPL	Lesser General Public License
LNI 4.0	Labs Network I 4.0
M2M	Machine-2-machine
MOM	Manufacturing operations management
MPL	Mozilla Public License
MRK	*Mensch-Roboter-Kollaboration* (human-robot collaboration)
NA/NIA	DIN Standards Committee on Information Technology and Selected Applications
NAMUR	User Association for Automation in Process Industries
NIST	National Institute for Standards and Technology (USA)
NLF	New Legislative Framework
DNS	German Standardization Strategy
OGC	Open Geospatial Consortium

OMG	Object Management Group
OPC-UA	Open Platform Communications – Unified Architecture
OpenAAS	Open Asset Administration Shell
OT	Operational Technologies
PAiCE	Platforms, Additive Manufacturing, Imaging, Communication, Engineering
PAS	Publicly Available Specification
PPP	Public Private Partnership
RAMI 4.0	*Referenzarchitekturmodell Industrie 4.0* (Reference architecture model Industrie 4.0)
RDF	Resource Description Framework
RoboPORT	*Crowd-Engineering-Plattform für Robotik* (Crowd-Engineering platform for robotics)
RM-SA	*Referenzmodell-Systemarchitektur* (Reference model for system architecture)
ROSIN	*Qualitätsgesicherte ROS-Industrial-Softwarekomponenten* (Quality-assured ROS industrial software components)
SC	Standards committee
SCI 4.0	Standardization Council I 4.0
SDO	Standards Developing Organization
SemAnz40	*Semantische Allianz 4.0* (Semantic Alliance 4.0)
SeRoNet	*Service Roboter Netzwerk* (Service Robot Network)
SG	*Strategiegruppe* (Strategy Group)
SIL	Safety Integrity Level
SMCC	Smart Manufacturing Coordinating Committee (ISO)
SMB	Standardization Management Board (IEC)
SOA	*Service-orientierte Architektur* (Service-oriented architecture)
SSO	Standards Setting Organization
SyC SM	System Committee Smart Manufacturing (IEC)
TACNET 4.0	*Taktiles Internet – Konsortium* (Tactile Internet – Consortium)
TC	Technical Committee
TCP	Transmission Control Protocol
TR	Technical Report
TS	Technical Specification
UK	*Unterkomitee* (Subcommittee)
UML	Unified Modelling Language
VDE	*Verband der Elektrotechnik, Elektronik und Informationstechnik e. V.* (Association for Electrical, Electronic & Information Technologies)
VDE AR	VDE Application rule
VDI	*Verein Deutscher Ingenieure e. V.* (Association of German Engineers)
VDI/VDE GMA	*VDI/VDE Gesellschaft Mess- und Automatisierungstechnik* (VDI/VDE Society for Measurement and Automatic Control)
VDMA	*Verband Deutscher Maschinen- und Anlagenbau e. V.* (German Engineering Federation)
VV	Administrative regulation
VWS	Administration shell
VWSiD	Administration shell in detail
W3C	World Wide Web Consortium

WG	Working Group
WTO	World Trade Organization
WoT	Web of Things
XML	Extensible Markup Language
ZDKI	*Zuverlässige drahtlose Kommunikation* (reliable wireless communication)
ZVEI	*ZVEI Zentralverband Elektrotechnik- und Elektronikindustrie e. V.* (Central Association of the Electrical and Electronics Industry)

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List of sources and references

[1] Plattform Industrie 4.0, Details of the Asset Administration Shell Part 1 – The exchange of information between partners in the value chain of Industrie 4.0, [Online], 2018

[2] DIN Deutsches Institut für Normung e. V., Die Deutsche Normungsstrategie [Online], März 2017

[3] Plattform Industrie 4.0, *Leitbild 2030 für Industrie 4.0: Digitale Ökosysteme global gestalten.* [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/Leitbild-2030-f%C3%BCr-Industrie-4.0.pdf? __blob=publicationFile&v=10## (accessed: Jan. 14 2020).

[4] Bundesministerium für Wirtschaft und Energie (BMWi), *Das Projekt GAIA-X: Eine vernetzte Dateninfrastruktur als Wiege eines vitalen, europäischen Ökosystems.* [Online]. Available: https://www.bmwi.de/Redaktion/DE/Publikationen/Digitale-Welt/das-projekt-gaia-x.html## (accessed: Feb. 20 2020).

[5] OPC Foundation, *OPC-F Working Groups.* [Online]. Available: https://opcfoundation.org/about/working-groups/opcf-wg/## (accessed: Jan. 14 2020).

[6] R. Heidel, M. Hoffmeister, M. Hankel, and U. Döbrich, Eds., *Industrie4.0 Basiswissen RAMI4.0: Referenzarchitekturmodell mit Industrie4.0-Komponente,* 1st ed. Berlin, Berlin, Wien, Zürich: VDE Verlag GmbH; Beuth Verlag GmbH, 2017. [Online]. Available: https://content-select.com/de/portal/media/view/58a1b07c-9f54-4f96-80ea-0d61b0dd2d03

[7] Ivar Jacobson, Ian Spence, Kurt Bittner, *Learn the Agile Way to Do Use Cases: The Guide to Succeeding with Use Cases.* Use-Case 2.0. [Online]. Available: https://www.ivarjacobson.com/publications/white-papers/use-case-ebook## (accessed: Jan. 14 2020).

[8] Plattform Industrie 4.0, *Landkarte »Anwendungsbeispiele Industrie 4.0«.* [Online]. Available: https://www.plattform-i40.de/PI40/Navigation/Karte/SiteGlobals/Forms/Formulare/karte-anwendungs-beispiele-formular.html?oneOfTheseWords=Suchbegriff+eingeben## (accessed: Jan. 14, 2020).

[9] Shi-Wan Lin (Thingswise), Brett Murphy (RTI), Erich Clauer(SAP), Ulrich Loewen (Siemens), Ralf Neubert (Schneider Electric), Gerd Bachmann (VDI), MadhusudanPai (Wipro), Martin Hankel (Bosch Rexroth), *Architecture Alignment and Interoperability: An Industrial Internet Consortium and Plattform Industrie 4.0 Joint Whitepaper.* IIC: WHT: IN3:V1.0: PB:20171205. [Online]. Available: https://www.iiconsortium.org/pdf/JTG2_Whitepaper_final_20171205.pdf## (accessed: Jan. 14, 2020).

[8] Industrial Internet Consortium, *Industrial Internet Reference Architecture V1.9.* [Online]. Available: https://www.iiconsortium.org/pdf/IIRA-v1.9.pdf## (accessed: Jan. 14, 2020).

[9] Plattform Industrie 4.0, *Aspects of the Research Roadmap in Application Scenarios.* Working Paper. [Online]. Available: https://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/aspects-of-the-research-roadmap.pdf%3F__blob%3DpublicationFile%26v%3D10## (accessed: Jan. 14, 2020).

[10] Plattform Industrie 4.0, *Benefits of Application ScenarioValue-Based Service.* Working Paper. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/benefits-application-scenario.pdf? __blob=publication File&v=7## (accessed: Jan. 14, 2020).

[11] *VDI Status Report Seamless and Dynamic Engineering of Plants.* Application Scenario SDP. [Online]. Available: https://www.vdi.de/ueber-uns/presse/publikationen/details/vdi-status-report-seamless-and-dynamic-engineering-of-plants## (accessed: Dec. 12, 2019).

[12] Plattform Industrie 4.0, *Digitale Geschäftsmodelle für die Industrie 4.0.* Ergebnispapier. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/digitale-geschaefts-modelle-fuer-industrie-40.pdf? __blob=publicationFile&v=7## (accessed: Jan. 14 2020).

[13] Standardization Council Industrie 4.0, DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE, *Use Case "Equipment Lifecycle Management": Sub-Working Group Industrie 4.0/Intelligent Manufacturing of the Sino-German Standardisation Cooperation Commission.* [Online]. Available: https://sci40.com/files/assets_sci40.com/img/sci40/190506_AK_EquipmentLifeCycleManagement.pdf## (accessed: Dec. 12 2019).

[14] GLOBALPROJEKT Qualitätsinfrastruktur, Ed., "Unterarbeitsgruppe Industrie 4.0: Ansätze für Normungsarbeit vertieft," Dec. 2018. Accessed: Jan. 14 2020. [Online]. Available: https://www.gpqi.org/news_de-details/unterarbeitsgruppe-industrie-4-0-ansaetze-fuer-normungsarbeit-vertieft.html

[15] Plattform Industrie 4.0, *Usage Viewpoint of Application Scenario Value-Based Service.* Discussion Papier. [Online]. Available : https://www.plattform-i40.de/I40/Redaktion/DE/Downloads/Publikation/hm-2018-usage-viewpoint.pdf ? __blob=publication File&v=8## (accessed: Jan. 14 2020).

[16] Plattform Industrie 4.0, *Usage View of Asset Administration Shell.* Discussion Papier. [Online]. Available : https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/2019-usage-view-asset-administration-shell.pdf? __blob=publication File&v=6## (accessed : Jan. 14 2020).

[17] Plattform Industrie 4.0, *Industrie 4.0 Plug-and-Produce for Adaptable Factories: Example Use Case Definition, Models, and Implementation.* Working Papier. [Online]. Available: https://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation/Industrie-40-Plug-and-Produce.pdf? __blob=publicationFile&v=7## (accessed: Jan. 14, 2020).

[18] Robot Revolution Initiative, *International Standardization Collaboration Progress Report: WG1: "Functional Viewpoint of Application Scenario Value-Based Service".* based on the joint statement between Plattform Industrie 4.0 and RRI. [Online]. Available: https://www.jmfrri.gr.jp/english/document/library/877.html## (accessed: Jan. 14, 2020).

[19] R. Heidel, M. Hoffmeister, and M. Hankel, *Industrie 4.0: The reference architecture model RAMI 4.0 and the Industrie 4.0 component,* 1st ed., 2019.

[20] NAMUR, *Willkommen bei der Interessengemeinschaft Automatisierungstechnik der Prozessindustrie*. [Online]. Available: https://www.namur.net/de/## (accessed: Feb. 20, 2020).

[21] The Open Group, *About Us.* [Online]. Available: https://www.opengroup.org/## (accessed: Feb. 20, 2020).

[22] NAMUR, *NAMUR Open Architecture.* Accessed: Jan. 14, 2020. [Online]. Available: https://www.namur.net/de/fokusthemen/namur-open-architecture.html

[23] International Data Spaces Association, *About the International Data Spaces Association.* [Online]. Available: https://www.internationaldataspaces.org/## (accessed: Feb. 20 2020).

[24] VDMA, *Interoperabilität durch standardisierte Merkmale: Neuer Leitfaden des VDMA ab sofort verfügbar.* [Online]. Available: https://sud.vdma.org/viewer/-/v2article/render/39398565## (accessed: Jan. 14, 2020).

[25] VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, *Anwendungsszenario DDA – Durchgängiges und dynamisches Engineering von Anlagen.* Statusreport. [Online]. Available: http://jahresbericht.vdi.de/fileadmin/user_upload/VDI-Statusreport_Anwendungsreport_DDA_-_Durchgaengiges_und_dynamisches_Engineering_von_Anlagen.pdf## (accessed: Jan. 14, 2020).

[26] Gesellschaft für Umweltsimulation GUS e. V., *Home: Willkommen bei der GUS e. V.!* [Online]. Available: https://www.gus-ev.de/## (accessed: Jan. 14 2020).

[27] Plattform Industrie 4.0, *Verwaltungsschale in der Praxis: Wie definiere ich Teilmodelle, beispielhafte Teilmodelle und Interaktion zwischen Verwaltungsschalen.* Diskussionspapier. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/2018-verwaltungsschale-im-detail.pdf? __blob=publicationFile&v=10## (accessed: Jan. 14 2020).

[28] Plattform Industrie 4.0, *Details of the Asset Administration Shell: Part 1-The exchange of information between partners in the value chain of Industrie 4.0 (Version 2.0).* Specification. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/Details-of-the-Asset-Administration-Shell-Part1.pdf? __blob=publicationFile&v=3## (accessed: Jan. 14, 2020).

[29] Plattform Industrie 4.0, *Verwaltungsschale in der Praxis: Wie definiere ich Teilmodelle, beispielhafte Teilmodelle und Interaktion zwischen Verwaltungsschalen.* Diskussionspapier. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/2019-verwaltungsschale-in-der-praxis.pdf? __blob=publicationFile&v=7## (accessed: Jan. 14 2020).

[30] Semantische Allianz für Industrie 4.0, *SemAnz40: Semantische Allianz für Industrie 4.0.* [Online]. Available: https://industrie40.vdma.org/documents/4214230/21871937/SemAnz40_1510217473136.pdf/dc1cc7f4-42f4-4086-9d38-38caa91f6f0e## (accessed: Jan. 14, 2020).

[31] ZVEI – Zentralverband Elektrotechnik und Elektronikindustrie e. V., *Antrieb 4.0 – Vision wird Realität: Merkmale, Daten und Funktionen elektrischer Antriebssysteme in Industrie 4.0 für Hersteller, Maschinenbauer und Betreiber.* [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2018/November/Antrieb_4.0_-_Vision_wird_Realitaet_-_erweiterte_Auflage/ZVEI_BR_Vision_Antrieb_4.0_2018_DOWNLOAD.pdf## (accessed: Jan. 14 2020).

[32] Ulrike Parson, *iiRDS – der neue Auslieferungsstandard für die Technische Dokumentation.* [Online]. Available: https://www.parson-europe.com/de/wissensartikel/427-iirds-auslieferungsstandard-technische-dokumentation.html## (accessed: Feb. 20, 2020).

[33] *Terms of Reference (ToR) for ETSI TC MTS TST WG (Testing).*

[34] ETSI, *ETSI Portal.* [Online]. Available: https://portal.etsi.org/tb.aspx? tbid=860&SubTB=860## (accessed: Jan. 12, 2020).

[35] ETSI, *Testing, Interoperability and Technical Quality.* [Online]. Available: https://portal.etsi.org/Services/Centre-for-Testing-Interoperability## (accessed: Jan. 14, 2020).

[36] Bitkom Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V., *IoT-Plattformen – aktuelle Trends und Herausforderungen: Faktenpapier.* Handlungsempfehlungen auf Basis der Bitkom Umfrage 2018. [Online]. Available: https://www.bitkom.org/sites/default/files/file/import/180424-LF-IoT-Plattformen-online.pdf

[37] *Digital Reality in Zero Defect Manufacturing: QU4LITY.* Grant agreement ID: 825030. [Online]. Available: https://cordis.europa.eu/project/id/825030## (accessed: Dec. 12, 2019).

[38] "FabOS – offenes, verteiltes, echtzeitfähiges und sicheres Betriebssystem für die Produktion," 2019. Accessed: Dec. 12, 2019. [Online]. Available: https://www.fab-os.org/

[39] OpenStack, *The OpenStack Foundation.* [Online]. Available: https://www.openstack.org/foundation/## (accessed: Jan. 14, 2020).

[40] Apache Software Foundation, *The World's Largest Open Source Foundation.* [Online]. Available: https://www.apache.org/## (accessed: Dec. 12 2019).

[41] Plattform Industrie 4.0, *Plattform Industrie 4.0: Die Verwaltungsschale im Detail.* von der Idee zum implementierbaren Konzept. [Online]. Available : https://www.plattform-i40.de/I40/Redaktion/DE/Downloads/Publikation/verwaltungsschale-im-detail-pr%C3%A4sentation.pdf? __Bob=publication-File&v=3## (accessed: Jan. 14 2020).

[42] Plattform Industrie 4.0, *Beziehungen zwischen I4.0-Kompo-nenten – Verbundkomponenten und intelligente Produktion: Fortentwicklung des Referenzmodells für die Industrie 4.0–Komponente SG Modelle und Standards.* Erlebnispapier. [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2017/Juni/Beziehungen_zwischen_I4.0_Komponenten/Beziehungen-zwischen-I4.0-Komponenten-zvei.pdf## (accessed: Jan. 14 2020).

[43] eCl@ss, *eCl@ss IN DER ANWENDUNG -USE CASES UND BEST PRACTICE.* [Online]. Available: https://www.eclass.eu/fileadmin/downloads/ecl_BestPractice-de.pdf## (accessed: Jan. 14, 2020).

[44] eCl@ss, *MIT DATEN UND SEMANTIK AUF DEM WEG ZUR Industrie 4.0.* Ein Whitepaper des eCl@ss e.V. [Online]. Available: https://www.eclass.eu/fileadmin/downloads/ecl-Whitepaper_2018_DE_klein.pdf## (accessed: Jan. 14, 2020).

[45] W3C, *Web of Things Working Group Charter.* [Online]. Available: https://www.w3.org/2016/12/wot-wg-2016.html## (accessed: Jan. 14, 2020).

[46] W3C, *Web of Things (WoT) Architecture: W3C Candidate Recommendation 6 November 2019.* [Online]. Available: https://www.w3.org/TR/wot-architecture/## (accessed: Jan. 14, 2020).

[47] IANA, *Link Relations.* [Online]. Available: https://www.iana.org/assignments/link-relations/link-relations.xhtml## (accessed: Jan. 14, 2020).

[48] OASIS, *MQTT: OASIS Standard.* [Online]. Available: https://docs.oasis-open.org/mqtt/mqtt/v3.1.1/os/mqtt-v3.1.1-os.html## (accessed: Jan. 14, 2020).

[49] S. Bradner, *Key words for use in RFCs to Indicate Requirement Levels.: Best Current Practice.* [Online]. Available: https://tools.ietf.org/html/rfc2119## (accessed: Jan. 14, 2020).

[50] T. Berners-Lee, R. Fielding, and L. Masinter, *Uniform Resource Identifier (URI): Generic Syntax: Internet Standard.* [Online]. Available: https://tools.ietf.org/html/rfc3986## (accessed: Jan. 14, 2020).

[51] M. Duerst and M. Suignard, *Internationalized Resource Identifiers (IRIs): Proposed Standard.* [Online]. Available: https://tools.ietf.org/html/rfc3987## (accessed: Jan. 14, 2020).

[52] T. Hansen, T. Hardie, and L. Masinter, *Guidelines and Registration Procedures for New URI Schemes: Best Current Practice.* [Online]. Available: https://tools.ietf.org/html/rfc4395## (accessed: Jan. 14, 2020).

[53] E. D. Crocker and P. Overell, "Augmented BNF for Syntax Specifications: ABNF: Internet Standard," IETF, Jan. 2008. Accessed: Jan. 14, 2020. [Online]. Available: ttps://tools.ietf.org/html/rfc5234

[54] N. Freed, J. Klensin, and T. Hansen, *Media Type Specifications and Registration Procedures: Best Current Practice.* [Online]. Available: https://tools.ietf.org/html/rfc6838## (accessed: Jan. 12, 2020).

[55] C. Bormann and P. Hoffman, "Concise Binary Object Representation (CBOR): Proposed Standard," IETF, Oct. 2013. Accessed: Jan. 12, 2020. [Online]. Available: https://tools.ietf.org/html/rfc7049

[56] E. R. Fielding and E. J. Reschke, *Hypertext Transfer Protocol (HTTP/1.1): Semantics and Content: Proposed Standard.* [Online]. Available: https://tools.ietf.org/html/rfc7231## (accessed: Jan. 14, 2020).

[57] Z. Shelby, K. Hartke, and C. Bormann, *The Constrained Application Protocol (CoAP): Proposed Standard.* [Online]. Available: https://tools.ietf.org/html/rfc7252## (accessed: Jan. 14, 2020).

[58] B. Leiba, "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words: Best Current Practice," IETF, May. 2017. Accessed: Jan. 12, 2020. [Online]. Available: https://tools.ietf.org/html/rfc8174

[59] E. T. Bray, *The JavaScript Object Notation (JSON) Data Interchange Format: Internet Standard.* [Online]. Available: https://tools.ietf.org/html/rfc8259## (accessed: Jan. 14, 2020).

[60] M. Nottingham, *Web Linking: Proposed Standard.* [Online]. Available: https://tools.ietf.org/html/rfc8288## (accessed: Jan. 14, 2020).

[61] Sebastian Käbisch and Takuki Kamiya, *Web of Things (WoT) Thing Description: W3C Candidate Recommendation 6 November 2019.* W3C Working Draft. [Online]. Available: https://www.w3.org/TR/wot-thing-description/## (accessed: Jan. 14, 2020).

[62] Institut für AutomatisierungstechnikHelmut-Schmidt-Universität/Universität der Bundeswehr Hamburg, *Semantik für Industrie 4.0-Systeme: Die Basis für den Informationsaustausch in Industrie 4.0-Anwendungsszenarien.* [Online]. Available: https://www.eclass.eu/fileadmin/images/content/projekte/semanz/Broschuere_Semanz40.pdf## (accessed: Jan. 14, 2020).

[63] Wolfgang Ahrens, Hasso Drathen, Oskar Kroll, Günter Löffelmann, Peter Zgorzelski, *Standardisierte Merkmale als Schlüssel für den unternehmens-weiten Datenaustausch im Engineering-Umfeld.* [Online]. Available: https://www.eclass.eu/static/documents/wiki/prolist/2006/EKA206_01.pdf## (accessed: Jan. 14, 2020).

[64] 5G-ACIA, "Integration of Industrial Ethernet Networks with 5G Networks," (White Paper), November 2019. Accessed: Dec. 12, 2019. [Online]. Available: https://www.5g-acia.org/fileadmin/5G-ACIA/Publikationen/5G-ACIA_White_Paper_Integration/WP_5G_Integration_of_Industrial_Ethernet_Networks_with_5G_Networks__Download_19.11.19.pdf

[65] *IEC/EN 62657-1:2015 "Industrial communication networks – Wireless communication networks – Part 1: Wireless communication requirements and spectrum considerations"*

[66] *IEC/EN 62657-2 Ed.2.0:2017 – "Industrial communication networks – Wireless communication networks – Part 2: Coexistence management"*

[67] 5G-ACIA, "A 5G Traffic Model for Industrial Use Cases (White Paper)," Nov. 2019.

[68] *VDI/VDE 2192 Blatt 1 „Quality of Service – Beschreibung und Beispiele."*, Gründruck 2019.

[69] VDI/VDE 2185 Blatt 4, *„Funkgestützte Kommunikation in der Automatisierungstechnik Messtechnische Performancebewertung von Funklösungen für industrielle Automatisierungsanwendungen"*, 2019.

[70] 5G-ACIA, "Selected Testing and Validation Considerations for Industrial Communication with 5G Technologies," (White Paper), Nov. 2019.

[71] Bundesnetzagentur, "Verwaltungsvorschrift für Frequenzzuteilungen für lokale Frequenznutzungen im Frequenzbereich 3.700-3.800 MHz: VV Lokales Breitband," Nov. 2019.

[72] 5G-ACIA, "5G Non-Public Networks for Industrial Scenarios," White Paper, Jul. 2019.

[73] *IEC 60802: Time-sensitive networking profile for industrial automation*

[74] Plattform Industrie 4.0, *The Asset Administration Shell: Implementing digital twins for use in Industrie 4.0: A starter kit for developers.* [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/EN/Downloads/Publikation/VWSiD%20V2.0.html## (accessed: Jan. 14, 2020).

[75] Bundesministerium für Wirtschaft und Energie (BMWi), *Positionspapier – Interoperabilität: Interoperabilität – Unsere Vision für Industrie 4.0: Maschinen sprechen in vernetzten digitalen Ökosystemen interoperabel miteinander.* [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/Positionspapier-Interoperabilität.pdf?__blob=publicationFile&v=3## (accessed: Jan. 14, 2020).

[76] Plattform Industrie 4.0, *Weiterentwicklung des Interaktionsmodells für Industrie 4.0-Komponenten.* Diskussionspapier. [Online]. Available : https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/interaktionsmodell-i40-komponenten-it-gipfel.pdf?__blob=publication File&v=5## (accessed: Jan. 14 2020).

[77] *German Standardization Roadmap Industrie 4.0.* DIN/DKE – Roadmap. [Online]. Available: https://www.din.de/blob/65354/57218767bd6da1927b181b9f2a0d5b39/roadmap-i4-0-e-data.pdf## (accessed: Dec. 12 2019).

[78] VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, *Industrie 4.0 – Begriffe/Terms.* [Online]. Available: https://www.vdi.de/ueber-uns/presse/publikationen/details/industrie-40-begriffeterms## (accessed: Jan. 14, 2020).

[79] Plattform Industrie 4.0, *Struktur der Verwaltungsschale: Fortentwicklung des Referenzmodells für die Industrie 4.0-Komponente.* Ergebnispapier. [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2016/april/Struktur_der_Verwaltungsschale/Struktur-der-Verwaltungsschale.pdf## (accessed: Jan. 14, 2020).

[80] Christian Diedrich et.al, *Semantic interoperability: challenges in the digital transformation age: IEC White Paper.* [Online]. Available: https://www.iec.ch/whitepaper/## (accessed: Jan. 14, 2020).

[81] ETSI, *ETSI TR 103 535 V0.2.2 (2019-03): SmartM2M; Guidelines for using semantic interoperability in the industry.* Technical Report. [Online]. Available: https://docbox.etsi.org/SmartM2M/Open/AIOTI/ST547/Draft%20TR%20103%20535v0.2.2%20consultation.pdf## (accessed: Dec. 12, 2019).

[82] *ISO IEC/CD 21823-2 "Internet of Things (IoT) – Interoperability for IoT Systems – Part 2: Transport interoperability*

[83] *ISO/IEC 21823-3 Internet of Things (IoT) – Interoperability for IoT Systems – Part 3: Semantic interoperability*

[84] ETSI, *ETSI GS ISI 006 V1.1.1 (2019-02): Information Security Indicators (ISI); An ISI-driven Measurement and Event Management Architecture (IMA) and CSlang – A common ISI Semantics Specification Language.* Group Specification. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/ISI/001_099/006/01.01.01_60/gs_isi006v010101p.pdf## (accessed: Jan. 14, 2020).

[85] Plattform Industrie 4.0, Glossar. [Online]. Available: https://www.plattform-i40.de/PI40/Navigation/DE/Industrie40/Glossar/glossar.html## (accessed: Jan. 14, 2020).

[86] Plattform Industrie 4.0, *Details of the Asset Administration Shell: Part 1 – The exchange of information between partners in the value chain of Industrie 4.0 (Version 1.0).* Specification. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/2018-verwaltungsschale-im-detail.pdf? __blob=publication File&v=8## (accessed: Jan. 14, 2020).

[87] W. Hacker, *Allgemeine Arbeitspsychologie: Psychische Regulation von Wissens-, Denk- und körperlicher Arbeit*, 2nd ed. Bern: Huber, 2005.

[88] C. Schlick, H. Luczak, and R. Bruder, Arbeitswissenschaft. Heidelberg: Springer, 2010. [Online]. Available: http://site.ebrary.com/lib/alltitles/docDetail.action? docID=10361974

[89] H.-J. Bullinger, D. Spath, H.-J. Warnecke, and E. Westkämper, *Handbuch Unternehmensorganisation: Strategien, Planung, Umsetzung,* 3rd ed. s.l.: Springer-Verlag, 2009. [Online]. Available: http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10288838

[90] M. Patterson, P. Warr, and M. West, "Organizational climate and company productivity: The role of employee affect and employee level," *Journal of Occupational and Organizational Psychology*, vol. 77, no. 2, pp. 193–216, 2004, doi: 10.1348/096317904774202144.

[91] aorzelskiGH, *admin-shell/aasx-package-explorer: aasx-package-explorer/builds/*. [Online]. Available: https://github.com/admin-shell/aasx-package-explorer/tree/master/builds## (accessed: Jan. 12, 2020).

[92] Eclipse Foundation, *Eclipse BaSyx.* [Online]. Available: https://projects.eclipse.org/projects/technology.basyx/downloads## (accessed: Jan. 14, 2020).

[93] ZVEI – Zentralverband Elektrotechnik und Elektronikindustrie e. V., *Automation und Digitalisierung: Potenzial und Einsatz von Blockchain- und Distributed-Ledger-Technologien in der Automatisierungstechnik.* Studie. [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2019/Februar/Blockchain-Studie/Blockchainstudie_14.02.19.pdf## (accessed: Jan. 14, 2020).

[94] *Funktionale Sicherheit sicherheitsbezogener elektrischer/elektronischer/programmierbarer elektronischer Systeme – Teil 3: Anforderungen an Software (IEC 61508-3:2010)*

[95] D. Steegmüller and M. Zürn, "Wandlungsfähige Produktionssysteme für den Automobilbau der Zukunft," in *Springer Reference Technik, Handbuch Industrie 4.0: Bd. 1: Produktion,* B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, Eds., 2nd ed., Berlin: Springer Vieweg, 2017, pp. 27–44. Accessed: Jan. 14 2020.

[96] Kasper, Björn, Stefan Voß, "Neue Anforderungen an die Sicherheitsnachweisführung von Maschinen und Anlagen im Kontext von Industrie 4.0," in *sicher ist sicher.* [Online]. Available: https://www.baua.de/DE/Angebote/Publikationen/Aufsaetze/artikel2093.pdf?__blob=publicationFile&v=3

[97] P. Liggesmeyer and M. Trapp, "Safety in der Industrie 4.0," in *Springer Reference Technik, Handbuch Industrie 4.0: Bd. 1: Produktion,* B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, Eds., 2nd ed., Berlin: Springer Vieweg, 2017, pp. 107–123.

[98] B. Kasper, "Maschinen und Anlagen in der digitalen Produktion – Neue Anforderungen an die Sicherheitsnachweisführung," in *baua: Aktuell.*

[99] K. Wickert, "Algorithmen: Chance und Herausforderung für die Maschinensicherheit," in *sicher ist sicher.*

[100] ZVEI – Zentralverband Elektrotechnik und Elektronikindustrie e. V., *Menschenzentrierte Künstliche Intelligenz in der Industrie: Zehn Handlungsempfehlungen für Deutschland und Europa: Positionspapier.* [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2018/Juli/Menschenzentrierte_Kuenstliche_Intelligenz_in_der_Industrie/Menschenzentrierte-Kuenstliche-Intelligenz-in-der-Industrie-Positionspapier.pdf## (accessed: Feb. 20, 2020).

[101] Big Data Value Association (BDVA), *Home.* [Online]. Available: http://www.bdva.eu/## (accessed: Feb. 20, 2020).

[102] European Union, *Artificial Intelligence: Public-Private Partnerships join forces to boost AI progress in Europe.* Shaping Europe's digital future. [Online]. Available: https://ec.europa.eu/digital-single-market/en/news/artificial-intelligence-public-private-partnerships-join-forces-boost-ai-progress-europe## (accessed: Feb. 20, 2020).

[103] Plattform Industrie 4.0, *Exemplification of the Industrie 4.0 Application Scenario Value-Based Service following IIRA Structure*. Working Paper. [Online]. Available: https://www.plattform-i40.de/PI40/Redaktion/DE/Downloads/Publikation/exemplification-i40-value-based-service.pdf? __blob=publicationFile&v=7## (accessed: Feb. 17, 2020).

[104] Bitkom Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V., *Digitalisierung gestalten mit dem Periodensystem der Künstlichen Intelligenz: Ein Navigationssystem für Entscheider.* [Online]. Available: https://www.bitkom.org/sites/default/files/2018-12/181204_LF_Periodensystem_online_0.pdf## (accessed: Feb. 17, 2020).

[105] DIN-Deutsches Institut für Normung e. V., *Ethikaspekte in der Normung und Standardisierung für Künstliche Intelligenz in autonomen Maschinen und Fahrzeugen*. [Online]. Available: https://www.din.de/de/din-und-seine-partner/presse/mitteilungen/ethikaspekte-in-der-normung-und-standardisierung-fuer-kuenstliche-intelligenz-in-autonomen-maschinen-und-fahrzeugen-322602## (accessed: Feb. 17, 2020).

[106] DIN-Deutsches Institut für Normung e. V., *DIN SPEC 92001-1:2019-04: Künstliche Intelligenz – Life Cycle Prozesse und Qualitätsanforderungen – Teil 1: Qualitäts-Meta-Modell.* [Online]. Available: https://www.beuth.de/de/technische-regel/din-spec-92001-1/303650673## (accessed: Feb. 17, 2020).

[107] Ralph Welge, Henrik J. Putzer, Janina Laurila-Dürsch und Stefan Heusinger, *Entwurfsmethodiken für Systeme mit Komponenten der Künstlichen Intelligenz*.

[108] P. Rauh and C. Wischusen, *Standards of the Future.*

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