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The Challenge of Implementing Digital Twins in Operating Value Chains

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Contents

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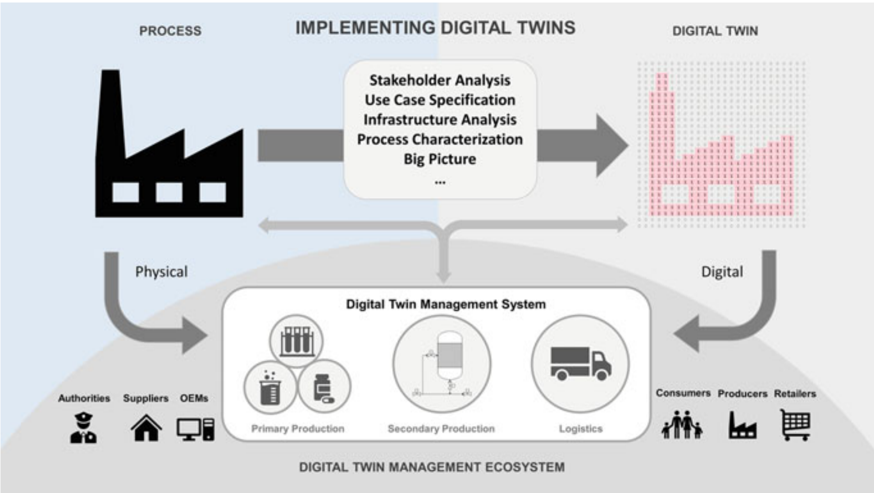
Abstract The concept of digital twins has become increasingly popular in recent years. To exploit their full potential, integration of systems and data across entire value chains is required. Implementing digital twins to newly built plants or production lines is challenging and even more complicated for currently operating production processes or factories. This chapter reviews and discusses strategies and tools to successfully implement digital twins into operating value chains in bioprocess and related industries. Furthermore, the implementation is exemplified with three recent case studies.

Graphical Abstract



Keywords Digital twin management systems, Ecosystems, Operating value chains, Standardization

1 Introduction

Industry 4.0 (I4.0), the new industrial revolution, refers to the emerging trends of digitization concepts for industries such as bioprocesses, food production, and operation value chains. Initiated by the German government, I4.0 comprises concepts and respective initiatives for digitalization and conception of modern goods manufacturing [1]. I4.0 includes various approaches to the digitization of new as well as the existing production processes. One central concept is the Digital Twin, which represents the virtual copy of the existing physical objects [2], these physical entities are also called assets. Academicians have abbreviated Digital Twin as DT [2, 3]. DTs can represent almost any aspect of an associated asset, ranging from highly aggregated information to a detailed description of its components and performance; even simulation models of assets can be part of a DT. The final result depends largely on the use cases, which are addressed with the DTs.

Applying DTs to newly built plants or production lines is challenging and even more complicated in operating production processes or factories. Heterogeneous processes have various requirements, which result in different obstacles in establishing a working Digital Twin Management System (DTMS), used to integrate different DTs. Plants and their processes often evolve, which leads to complexity. Inhomogeneous and even incompatible systems result in connectivity problems and imprecise interrelations. Following Rosen et al. [4], DTs are not just a collection of virtual objects, but require interrelations, connections, and structure within a DTMS to leverage the full potential.

Connectivity, modularity, and autonomy are key enablers of DTs [4]. They improve process development, production planning, process intelligence, production execution, and the individualization of products and equipment. DTs connect the virtual networks and systems with the real world. Furthermore, full trackability and traceability, which are essential for food safety, become feasible. Artificial intelligence (AI)-enabled concepts and technologies lead to state-of-the-art production concepts and the establishment of production intelligence. Finally, DTs, together with a DTMS, support companies to prepare for the challenges of I4.0. Kritzinger et al. [3] categorize a DT into a Digital Model and a Digital Shadow based on the level of integration. DTs comprise an automatic data flow between physical and virtual objects. Their functionality depends on the accuracy of the underlying semantic description, the assignment of relevant information, and a well-designed structure in the DTMS. Therefore, suitable techniques and standards must be applied. For example, the *Asset Administration Shell* (AAS) is a domain-independent standard of the German *Platform Industrie 4.0*, which specifies how to construct DTs, namely their data models and their interfaces, that allow efficient interaction in Industry 4.0 scenarios. It is being developed as a standardized software interface of any physical assets.

This chapter explains the strategies and tools to implement DTs into operating value chains or industrial processes and demonstrates its successful implementation with three case studies by analyzing the value chain, corresponding stakeholders, and the process as well as the primary infrastructure. From the initial step with an analysis of the stakeholder and DT goals to the final implementation, the chapter includes all necessary steps for successful execution. Figure 1 provides a graphical overview of the general implementation pathway which is outlined in the different sections of this chapter.

Notably, the status quo associated with the development of the future desired digitalized structure (DTs and DTMS) is illustrated. A physical model (physical picture) and a data model (virtual picture) of the considered value chain are also included showing the interrelations and interfaces among stakeholders. The physical

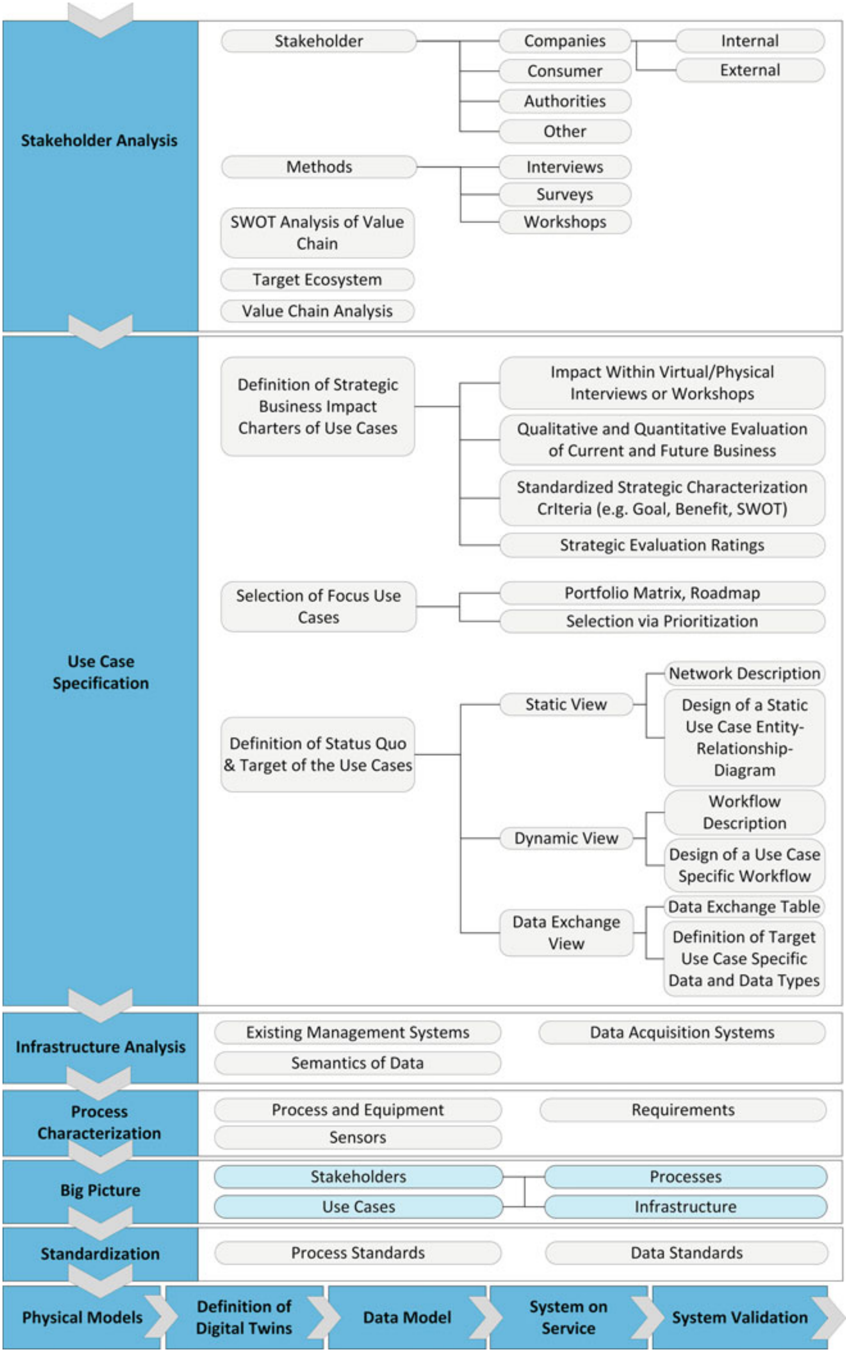


Fig. 1 Step-by-step process of implementing digital twins into an operating production or value chain

model includes the original equipment such as machines, sensors, and actuators as physical assets. The data model represents the advancement and comprises all data points that can be acquired from the relevant components of the physical production process. It also includes all management systems in the operating production process that are part of the DTMS. Notably, the data model also consists of the individual order of the DTs. In addition, this chapter reviews relevant standards that support the establishment of an operating DTMS and highlights future opportunities.

2 Industrial Bioprocesses and Corresponding Value Chains

Biological transformation processes determine our daily life. Nature developed various principles that are also applicable to industrial production processes. Process engineers use different bioprocess-related, procedural techniques, e.g., fermentation, to transform substrates to the desired consumer good. According to Liu [5], bioprocesses are present in the following industrial areas: biomaterials, health, biology, process industry, biofuel, and food. In particular, the production of food, pharmaceuticals, and biotechnological goods requires elaborate bioprocesses.

For these reasons, bioprocesses are elementary parts of value chains. A value chain adapts the production steps of a specific product to its ecosystem or the company's complete manufacturing process if only the corresponding parts of the value chain are considered. In order to depict the industrial perspective in a reasonable way, it is essential to evaluate the value chain as a whole. Thus, not only the bioprocesses should be considered but all other unit operations involved. For the production of bioproducts (e.g., food), several production steps are required. Exemplary processes in the food industry are the production of beer or yogurt, where fermentations are fundamental for their production. This chapter outlines in Sect. 7 several case studies that belong to the food industry and corresponding logistics.

A complete overview of the production environment is necessary to guarantee full interconnections of DTs within certain company areas or even among individual companies. In particular, tracking and tracing must consider all elements of the value chain.

3 Analysis of Operating Value Chains

A DTMS implementation usually starts with the value chain analysis of the associated ecosystem (Fig. 1). A value chain is analyzed by identifying the stakeholders, the operating production lines, what physical and virtual components need to comprise the DTMS, and the types of requirements. Subsequently, the use cases and targets of the DTMS, including the interfaces and connections between the stakeholders, need to be specified. Furthermore, the stakeholders' technical and virtual infrastructure must be analyzed. This helps in defining the process borders,

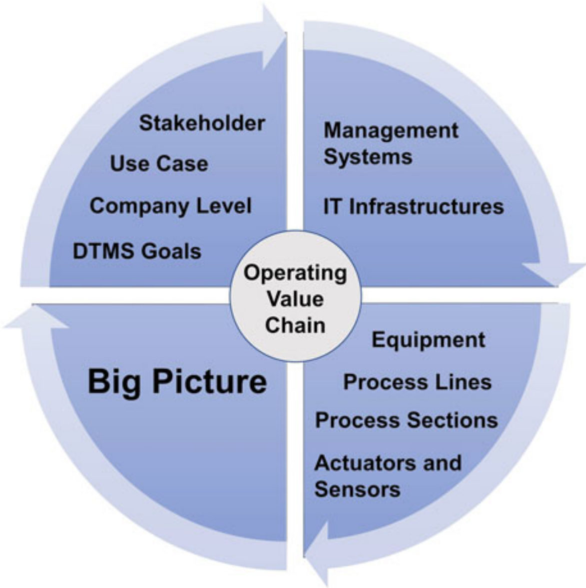


Fig. 2 Overview of value chain analysis

identifying the desired data points in the production process, and leading to overall standardization. In-depth knowledge of these factors is necessary to create a big picture of the entire structure of the DTMS (Fig. 2).

3.1 Stakeholders Analysis

Different stakeholders participate in the value chain and exert their influence. These members or groups perform numerous tasks, are responsible for particular tasks in the DTMS, and benefit from the system and associated tools. The stakeholder analysis depends on environmental conditions such as regional requirements and infrastructural conditions of a country (e.g., developing countries). The literature [6–10] outlines several considerable requirements and provides approaches for conducting a stakeholder analysis in compliance with the preexisting conditions.

Regarding a DTMS, stakeholders are distinguishable in company's internal as well as external groups. Internally, stakeholders include employees and managers with a given responsibility (e.g., production manager, warehouse manager, and quality manager). Externally, stakeholder groups consist of other companies (e.g., raw material suppliers), governmental organizations (e.g., food authorities), and customers. Therefore, the following specific aspects must be considered for DTMS:

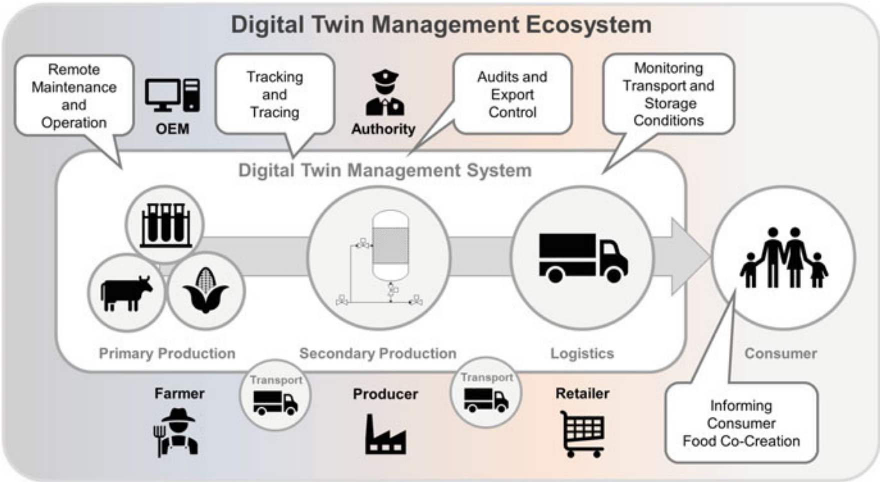


Fig. 3 Sharing digital twin data with stakeholders in a Digital Twin Management Ecosystem and corresponding tasks

– Scope of the DTMS: Is it designed for internal purposes only, or will it also involve the production processes of other companies in a business-to-business solution (B2B)?
– What companies, associations, and authorities will take part in it?
– Who is involved in the production process in the company internally (e.g., quality manager, operators, and logistics manager)?
– Is a business-to-customer (B2C) solution considered?

Following stakeholders' identification and distribution of relevant tasks, a stakeholder network is conceptualized. Figure 3 shows an exemplary bioprocess value chain, relevant stakeholders, and associated tasks.

3.2 Use Case Specification

Use cases refer to specific application examples of the planned system (e.g., the DTMS) and pursue specific goals. Additionally, they are ideal for testing the functionality of the system and pave the way for further applications. However, the actual reliability must be compared with all influencing parameters and always be subjected to a critical review [11, 12]. Use cases comprise defined targets and represent a system's behavior according to the users' requirements for reaching those targets. These users are individuals or groups and represent stakeholders. Each use case has distinct tasks and aims that must be achieved by applying a specific procedure. Use cases indicate DTs' responsibilities and are always named

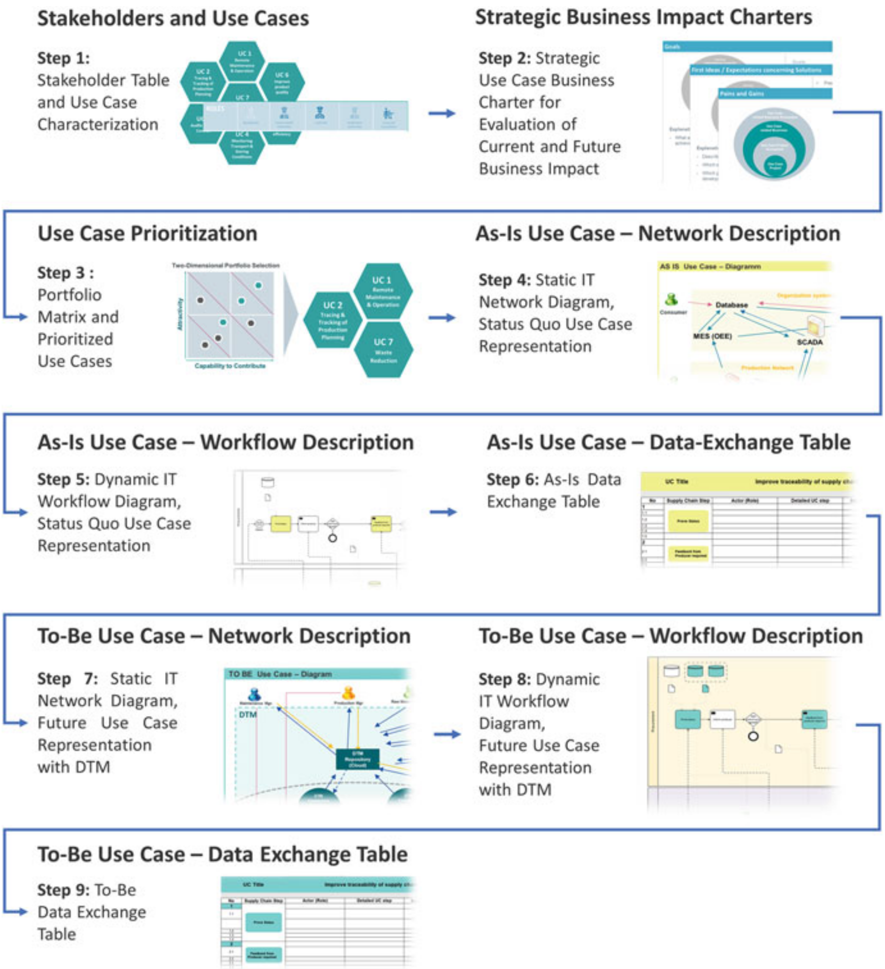


Fig. 4 Process for identification, selection, and description of use cases

according to their primary goals. Concerning whole value chains, the product trackability would be a model use case for implementing DTs. Besides, use cases illustrate all likely scenarios when a stakeholder acts using the respective system.

Use cases for DT-based application scenarios are described for the current situation (“As-Is”) or for the future (“To-Be”) and are designed with static (e.g., network diagrams) or dynamic (e.g., workflows) representations. They provide the basis for deriving requirements and the subsequent solution design (software development).

For defining use cases at a strategic and operational level, the following steps and Fig. 4 describe a detailed systematic approach. This systematic approach provides a comprehensive, condensed, multi-view, and consensual basis for quality-assured requirements engineering as a basis for all subsequent tasks, from data modeling to the development of DT-based software functions.

Step 1: Identification of Stakeholders and Use Cases

Based on a general understanding of the use cases, company internal stakeholders as well as external stakeholders of the ecosystem are identified. They contribute to the methods described in the steps 2–9.

Methods: Virtual or face-2-face interviews, surveys, workshops with design thinking, and creativity sessions

Results: Stakeholder table and use case characterization (short description)

Step 2: Definition of Strategic Business Impact for Use Cases

The current and future business impact for the identified use cases is analyzed.

Methods: Qualitative description and quantitative evaluation of strategic business impact is analyzed within interviews and workshops. Hereby standardized strategic issues (e.g. goals, benefits, and SWOT) and measurable criteria for strategic ratings are used.

Results: Strategic use case business charter

Step 3: Prioritization and Selection of Focus Use Cases

The use case candidates from step 1 and 2 are prioritized based on the evaluation results from step 2. Most attractive use cases are selected as focus use cases by all stakeholders.

Methods: Prioritization and selection methods, e.g. scoring methods, AHP (analytic hierarchy process)

Results: Portfolio matrix and prioritized use cases

Step 4: Definition of Status Quo (As-Is) Use Cases – Static view of IT assets

Definition of a static IT network diagram of As-Is focus use cases showing all relevant IT components (e.g., hardware, software), roles, actors, and their data-input/output relations.

Methods: Design of a static use case entity-relationship-diagram

Results: Static IT network diagram: As-Is Use Case Representation

Step 5: Definition of Status Quo (As-Is) Use Cases – Dynamic view of IT assets

Development of a workflow diagram of As-Is focus use cases showing logical sequence of activities of roles or actors, and their data input/output relations

Methods: Design of a use case specific workflow

Results: Dynamic IT workflow diagram: As-Is use case description

Step 6: Definition of Status Quo (As-Is) Use Cases – Data exchange view

Specification of data (e.g., data types, data attributes) exchanged by relevant actors.

Methods: Interviews and workshops on further data concretization

Results: As-Is data exchange table with detailed data specifications

Step 7: Definition of Future (To-Be) Use Cases – Static view of IT assets

Definition of a static IT network diagram of To-Be focus use cases (utilizing Digital Twin) showing all relevant IT components (hardware, software), roles, actors, and their data-input/output relations.
Methods: Design of a static use case entity-relationship-diagram
Results: Static IT network diagram: To-Be use case description

Step 8: Definition of Future (To-Be) Use Cases – Dynamic view of IT assets

Development of a workflow diagram of To-Be focus use cases (utilizing Digital Twin) showing logical sequence of activities of roles or actors and their data input/output relations
Methods: Design of a use case specific workflow
Results: Dynamic IT workflow diagram: To-Be use case description

Step 9: Definition of Future (To-Be) Use Cases – Data exchange view

Specification of data (e.g. data types, data attributes) exchanged by relevant actors.
Methods: Interviews and workshops on further data concretization
Results: To-Be data exchange table with detailed data specifications

In summary, the collaboratively elaborated results of all steps of this systematic approach provide a comprehensive and condensed basis (Big Picture, see Sect. 3.5) for a systematic methodology from requirements engineering and data modeling to the development of Digital Twin based software functions. Investment in infrastructure for digitalization must consider several highly ranked use cases: The return on investment may be high, and the investment for implementing an additional use case is usually not as significant as for establishing the infrastructure for the first use case. Several attractive use cases can be achieved only if DT data is shared among different stakeholders (Fig. 3).

3.3 Infrastructure Analysis

DTs are a sophisticated link between the virtual and the physical world, but their implementation is application-specific [3]. However, the following are the minimum requirements for the implementation:

– The digital environment (e.g., server and network structure)
– A standardized process
– Extent of automation level following the minimum requirements
– Definition of a minimum data structure for communication
– Expert, plant, machine, and product knowledge

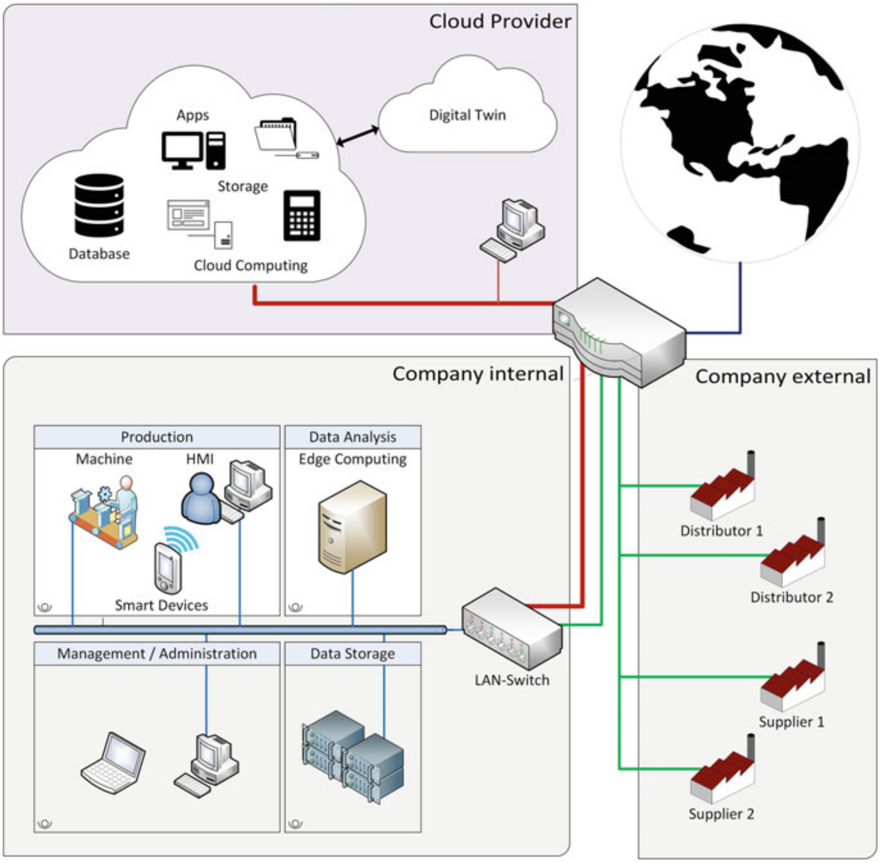


Fig. 5 A simple concept of essentials for IoT, edge computing, cloud computing, and Digital Twins

– Enabler technologies for physical system integration
– Definition of sensor, operational, and transactional data
– Definition of system granularity
– Connectivity of manual and automated tasks

Data sampling and communication must consider these minimum requirements in the planning phase (Fig. 5). The production line is linked to other departments such as administration, shipping, and other on-site facilities such as servers and databases, e.g. by using cloud services. The communication might address external company locations, sales partners, distributors, or suppliers. The all-inclusive DT is located in the cloud and uses its services (e.g., for data storage, databases, and service apps). The cloud and the DT (asset core) are linked to all aforementioned components. The cloud provider is responsible for the final hosting in the cloud.

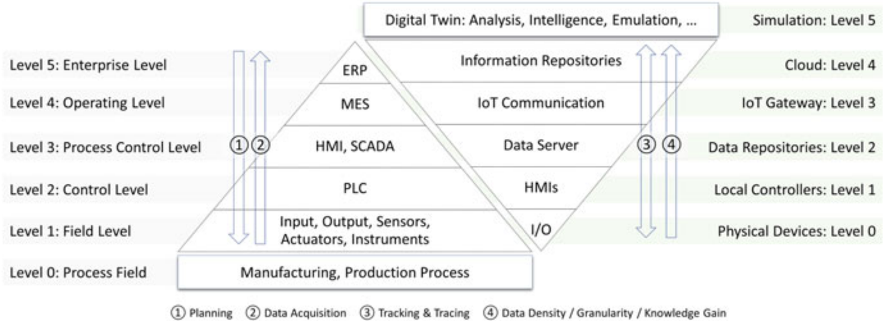


Fig. 6 Architecture of automation pyramid (Siepmann model based on DIN EN 62264 [15, 16]) in context to Digital Twins (adapted from [17])

Furthermore, the communication structure is critical for extensive networking within the company, enabling real-time data traffic between the DT and its counterparts (physical assets). A DTMS requires bidirectional communication. This interrelation can be implemented through a wired or wireless network and radio standards such as 5G. Notably, the 5G standard is widening possibilities in creating local area data networks to use mobile and rapid information exchange inside plants using smart mobile devices [13]. A well-established network is essential for the DT to share real-time data with physical assets such as control modules, sensors, machines, and human–machine interfaces (HMI).

Data communication must follow common language, universal communication, and standardized structure. The existing industrial communication protocols commonly used for process monitoring and control can be used for data communication. In practice, owing to the numerous companies acting worldwide, more than one format or communication protocol is commonly used in one production plant. Here, converters may translate the data into a dominating protocol.

HMIs are the link between the human operator and the DT. They integrate human intelligence and skills to improve efficiency [14]. By defining particular transfer points in the physical systems, HMIs can be implemented into the DT, which adds less automated or even offline modules to the system. Every manual input affects the system's consistency and should, therefore, be avoided.

The granularity of the DT can be determined within the network structure and connectivity of the physical assets. A simple DT is limited to a particular physical asset such as a product, administration task, single machine, or equipment. Increasing the granularity of the DT increases the number of linked physical assets. Therefore, DTs can be used to observe a single production process, or, according to the automation pyramid of Siepmann [15], DTs can be linked to field, control, process control, operating, and enterprise level. With increasing granularity, the amount of data, network traffic, and computational calculations increases. These details result in higher investment costs and thus lead to an improved process resolution. A holistic DT is the objective of modern intelligent systems.

Figure 6 shows the holistic approach of a cyber-physical system connected to the DT according to the automation pyramid of Siepmann [15, 16]. On the left, 0–5 describe the automation pyramid separated into strictly hierarchical company levels: 0 is the sensor/actuator level, characterized by simple and rapid data sampling; 1 is the field level, the interface to the production process; 2 is the control level; 3 is the process control level; 4 and 5 are the plant management and company levels, respectively, where production planning, production data acquisition, and order processing are conducted. The pyramid of the DT is illustrated on the right. Levels 0–1 contain the physical assets, where level 0 includes actuators, sensors, and equipment and level 1 provides additional functionality such as HMIs for the DT. Level 2 contains communication and data servers. Level 3 is the gateway between the physical assets and the DT, and all the other structures connected to the system. Levels 2 and 4 communicate over the gateway, whereby level 4 supports cloud-based databases with information from the physical assets and DT. Levels 0–4 allocate the required infrastructure for the DT. Level 5 consists of the digital core asset, the DT with all necessary apps such as simulation, emulation, and modeling. With increasing levels in the automation pyramid, the data flow increases. This correlation offers extensive networking, thus enabling the full capability of the DT.

The connection of levels 1–3 in the DT pyramid is achieved in production lines through hierarchy, whereby three levels of networking are distinguished: unit, system, and system of system (SoS) level [18]. The unit level is the smallest element and can comprise machine equipment, materials, or sensors. The system level is a combination of multiple unit levels, which can communicate and control each other by field bus, Ethernet, or 5G. SoS is composed of multiple system levels as in the collaboration of multiple production lines and combines all data of the production lifecycle.

3.4 Process Characterization

Process characterization requires a detailed analysis of all physical production equipment (including sensors) and the procedures to identify all the production parts that are linked with the product, or relevant for the supply of utilities (e.g., electricity, steam, and gases), or affect the process quality indirectly (e.g., cooling systems and logistics). The production departments and floors relevant for implementation into the DTMS must be defined. Within these individual sections, identification of equipment and defining of the process borders ensure the assignment of the process to the most appropriate subsections. Moreover, the defined process borders help to model the correct process sequence in the DTMS and reduce its overall complexity (Fig. 7).

In process engineering, a process consists of a sequence of several chemical, physical, or biological unit operations [19, 20]. Each unit operation aimed to convert, transport, or store raw materials or intermediates. Combining all process steps ensures the production of the desired good and its packaging. Industrial production

Fig. 7 The different steps of process analysis with exemplary components

processes can be categorized as batch, continuous, and discrete manufacturing [21]. A batch process represents a discontinuous production process that consists of various unit operations. In contrast, a continuous process runs through production without interruption, and raw materials and intermediates are processed by passing each production stage. Discrete parts manufacturing illustrates the production processes that create a specific quantity of intermediates. Once the specific quantity is achieved, further processing occurs. Accurate classification of the process is essential for selecting the appropriate standards and identifying the key process steps (unit operations).

Following the identification of all the relevant process components and their classification into "with product contact," "utilities-relevant," and other markings, their semantics must be defined. This terminology highlights the need for correct naming or numbering of the components, description of the process task, classification of the process relevance, and other designations that help in understanding their role in the DTMS. For these instructions, all the existing process descriptions are beneficial. Exemplary records are flow charts, SCADA-charts (Supervisory Control and Data Acquisition), illustrations from management systems, and results of laboratory management systems.

3.5 Composition of the Big Picture

The big picture provides the DTs' structure and architecture and comprises the DTMS as well as its connectors, functions, and the necessary physical model and data model. It is an integrated complete high-level vision of the "To-Be" system, depicting the desired future operation. It considers current trends (e.g., digitization), historical social perspective (e.g., consumer demands), economic perspective (e.g., influence of the market), and forecast (e.g., influence of artificial intelligence; effects of robots) as well as own objectives.

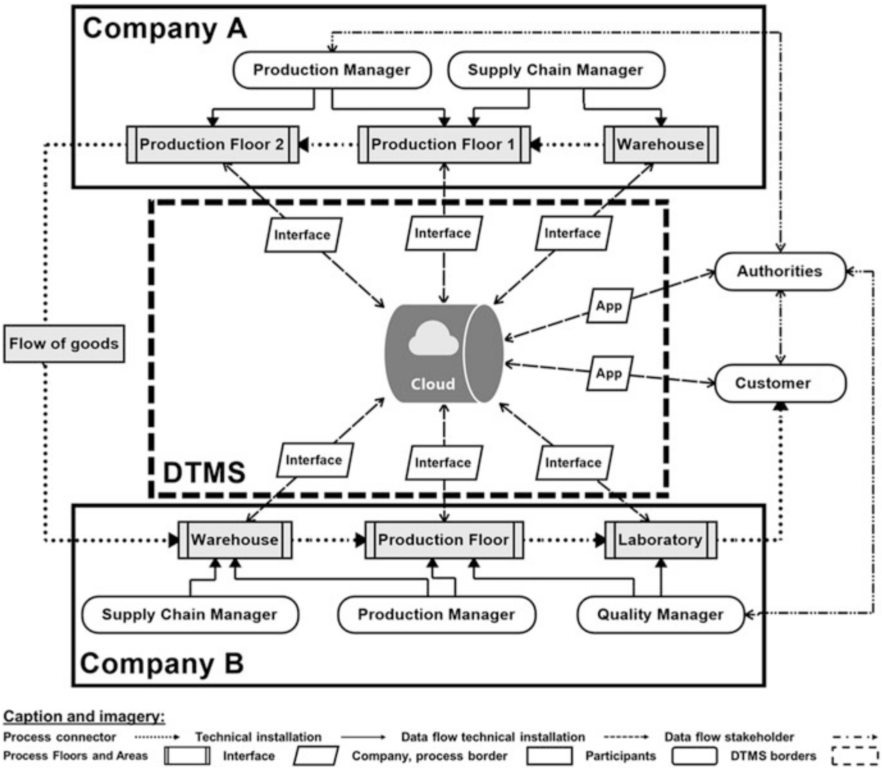


Fig. 8 Big picture of an exemplary DTMS with stakeholders

Here, the DTMS forms the core element consisting of the cloud storage, the relevant stakeholder interfaces, and the apps. In particular, the apps provide special tools (e.g., analysis and predictive tools) that enable the full potential of the system. Furthermore, it is important to link all participating elements to define the interrelations within the process borders and between the individual parties. Its creation also supports the comprehension of interrelations between stakeholders and inherent assets. Figure 8 illustrates an exemplary big picture consisting of two different companies by showing connections and data flows.

4 Standardization and Generation of Digital Twins

A DTMS merges multiple production systems and data points, whose origin plays an essential role because these data sets are of different quality and comprehensiveness. The combination of various production lines, independent plants, and even different companies results in different kinds of data sets. In the case of extensive data sets, a reasonable junction in the DTMS is unfeasible. This aspect is confirmed by Weyer et al. [22], who researched on modular, multi-vendor systems in the context of Industry 4.0. Therefore, there is a high demand for standardization and relevant norms. Furthermore, the use of a DTMS must comply with the corresponding legislation, for example, hygienic requirements or work safety concepts. These aspects are essential as a DTMS may also function as the basis for other concepts.

Standardization is a critical dimension of sustainable and efficient engineering. Standards specify the design features of equipment, create comparability between manufacturers, and help customers receive a safe product that complies with existing legislation. According to the *German Institute for Standardization* (DIN, Deutsches Institut für Normung e.V.) [23], standards are the universal language of engineering and facilitate free movement of goods. In a DTMS, standards facilitate a comparison of different data sets, production lines, plants, or even companies. They help create individual DTs and their application in a DTMS. Finally, standardization also provides the language that facilitates the communication between DTs. Lu et al. [24] emphasized the importance of standards for DTs by analyzing the state-of-the-art manufacturing domains.

4.1 Overview of Existing Standards

International, continental, and national organizations define the standards for the public. Globally, the *International Organization for Standardization* (ISO) for technical standards and the *International Electrotechnical Commission* (IEC) for standards with electrotechnical relevance function as the roof organizations. Currently, over 160 national standardization committees are members of the ISO [25]. The complexity of a DTMS, especially in B2B or B2C relations, challenges standardization as new technologies are emerging. However, national and international standardization organizations release new drafts for standards continuously. The ISO has been developing a series of standards for DTs. The series will include four different parts, definitions, suitable reference architectures, digital representation of physical manufacturing elements, and information exchange [26–29], and define the framework of DTs. Another ISO standard under development focuses on the visualization elements of DTs [30]. These standards are expected to gain significance for implementing DTs in the future.

Standardization of DTs requires distinction between process and data standards. Process standards must include definitions of physical objects such as equipment, machines, or connectors (e.g., pipes). Production types must be defined, and company-related properties standardized. Here, the *International Society of Automation* (ISA) and the *American National Standards Institute* (ANSI) offer suitable standards for production processes. Notably, the three standard series ISA-88, ISA-95, and ISA-106 include appropriate methods and tools for DT standardization [21, 31–46]. The standardization process also supports the analysis of the basic properties of a production line and its transferability into a DTMS.

With regard to data sets, different levels of the data hierarchy must be defined. Following the *German Electrical and Electronic Manufacturers' Association* (ZVEI, Zentralverband Elektrotechnik- und Elektronikindustrie e. V.) [47], the description of data sets emerges from the following aspects:

– Data type (e.g., real, bool, and array) and data format (e.g., XML and JSON)
– Data source (e.g., alarm value and measured value)
– Data semantics (e.g., manual or automatic process)
– Data display (e.g., numerical and curves)
– Aggregated illustration of data (e.g., faceplates and complex diagrams)
– Functional integration of data (e.g., controller and HMI link)

This ontology-driven approach helps the operator to understand the type of data visible, its origin, and meaning. The DTMS requires a semantic web structure that helps distinguish between DTs. Management execution systems (MES) can be combined with DTs, which lead to a full MES-driven approach. The requirements of management and control of the quality (ISO 9001), the energy (ISO 50001), and occupational health and safety (ISO 45001) can extend DTMS appropriately and create a comprehensive production system [48–50].

General management systems, as well as food safety, are feasible in a DTMS. Here, requirements, limit values, or legislation are applicable to DTs. Food safety management systems (e.g., ISO 22000), similar concepts and measures, such as HACCP (hazard analysis and critical control points), are also associated with the DTMS [51]. These supplements help monitor the hygiene and food safety status in the production, train employees with customized instructions, and avoid or at least react promptly in case of a food safety event. Moreover, authorities and audit organizations are likely to participate in DTMS. The ISO facilitates corresponding bodies and audits in this field [52]. If a DTMS focuses on tracing and tracking, ISO suggests principles and basic requirements [53].

4.2 Process Standardization

Given that a DTMS can be local or global, it is essential to identify and list all its relevant components. Typically, this process analysis includes a complex mix of various companies, plants, process types, equipment designs, connectors, and sensors. This section outlines how this heterogeneity can be standardized. First, this study helps to achieve a general application of the various processes into a DTMS. Second, an appropriate standard of communication must be established in all associated processes. The ISO offers suitable standards that are regularly updated. It is necessary to identify what processes will be implemented into the DTMS (see Sect. 3.4).

The main focus is on the process type. The ANSI/ISA-88 (or S88, SP88) covers batch processes and contains four interdependent parts. The IEC and national standardization organizations have published corresponding versions (e.g., IEC 61512-1 and DIN 61512) [54, 55]. The ISA-88 shows the possibilities of structuring procedural systems and equipment in levels. A level organization helps in greater flexibility and increased performance of the considered batch process. Part 1 [21] includes the terminology as well as the definitions of the entire production process and its modeling possibilities. Part 2 includes the structures of data and key communication [31] (see also Sect. 3.3). Part 3 [32] treats product recipe models and their method of definition. Part 4 [33] comprises the recording of batch production. Other standards belonging to the ISA-88 explain the implementation (e.g., packaging equipment), as well as recipe formats, and are also useful for developing DTMS [41, 56].

For a DTMS's basic construction and architecture, part 1 is the most critical standard for batch processes. The physical model can be derived from this standard. This model represents the physical structure and the essential connections of the DTMS. Hierarchical levels create a structure that forms the entire production process. From top to bottom, the physical model grows holistically – groups of production parts in a lower hierarchy form a part of the subsequent higher level. Thus, the entire production process is illustrated, and a logic structure of relevant processes with the corresponding subgroups emerges. Any DT can be derived from the emerging modeled structures; that is, each part of a hierarchy can also represent its own DT.

Furthermore, virtual relations, which lead to the data model, are based on the physical model. The physical model illustrates the rigid interrelations of batch production. Figure 9 gives an overview of the selected terminology and levels of the ISA-88, the assignment to specific physical production components, and the adaption in a DTMS.

Following Fig. 9, the structure and process-related architecture of the DTMS can be derived. The linkages between distinct DTs must be defined. For example, the link between the two DTs is achieved through pipes or conveyor belts. If there are valves that can monitor and record the time (e.g., timestamp of valve switching), the batches are trackable and traceable.

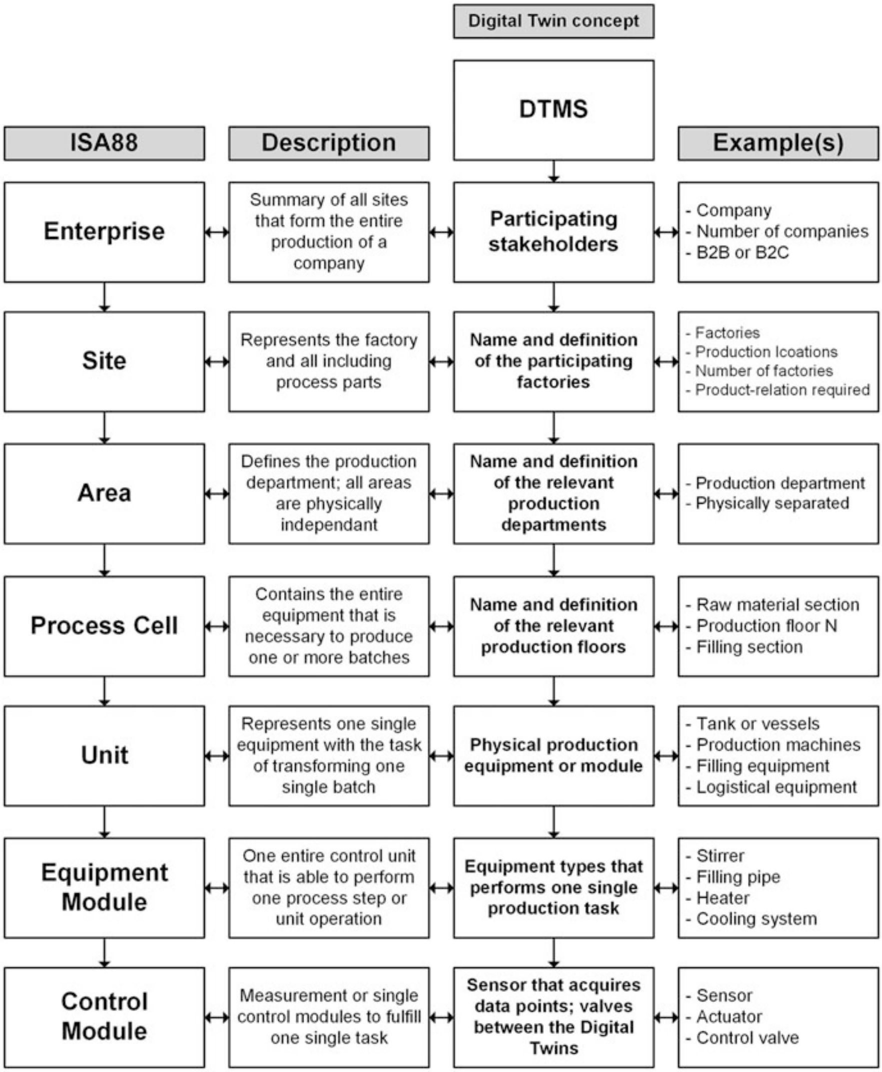


Fig. 9 Application of the ISA-88 physical model to standardize a process and implementation into a DTMS

The ISA-88 focuses on process cell, unit, equipment module, and control module. Terminology and background of enterprise, site, and area are defined in ISA-95. This standard deals with the integration of the corporate and operational management levels and is based directly on ISA-88. Besides batch production, it is also applicable to continuous and discrete production processes. The ISA-95 consists of seven parts including models, definitions, object model attributes, activity models, possibilities of management operations, business-to-manufacturing transactions, messaging services, and an alias service model [34–37, 39, 40, 45]. The international version of this standard is the IEC 62264, which is based on the works of ISA. With the help of ISA-95, various management systems can be applied to the DTMS. It also helps plan the access of various stakeholders or operators within the production process. In combination with ANSI/ISA-101.01-2015 [46], the possible methods of implementing HMIs help in the efficient control of the DTMS on-the-machine or with mobile devices. An additional standard combines the implementation of ISA-88 and ISA-95 [44].

For continuous production, the ISA-106 offers an in-depth alternative [42, 43]. In comparison to ISA-88 and ISA-95, this standard series offers elaborate physical models that help organize even complex processes. For example, it defines a variable state model as illustrated by a user with high flexibility.

4.3 Data Standardization

Industry 4.0 factories have physical machines, or components called assets, connected to software that visualize the entire production line or make own decisions. An asset is an organization's physical entity having either a perceived or an actual value [57]. For bioprocesses, these are machines or different plant facilities and their parts.

Interoperability is the basis for I4.0 and ensures open and plural markets. It is characterized by open standards. The German *Platform Industrie 4.0* (PI4.0) develops pre-competitive concepts and solutions for I4.0, implements them, and participates in international standardization processes through more than 10 international cooperation [58]. The PI4.0 AAS specification [59] is the basis for interoperability and a DT standard. The intention is to become the central, standardized "integration plug" of any asset to digital ecosystems, composed of multiple DTs. Using an AAS, all relevant assets speak a common language, which eases integration. Any physical item that provides relevant data may become an asset and in turn get an AAS. Therefore, it is considered as a data standard as well. For example, the operating data of a plant and the production process can be standardized throughout their life cycle by building AAS DTs, which may be integrated into a DTMS.

The data exchanged or made available via an AAS is described in a modular, manufacturer-neutral format with formally described semantics. It does not prescribe what data is provided, but how they are provided. The generic AAS data model is defined using Unified Modeling Language (UML) class diagrams. Using an AAS, the DTs data is organized into submodels. Therefore, the main classifications are as follows:

– *Submodels*, which are either predefined entirely or may be described using a standard pattern. An AAS may have any number of submodels.
– *Properties*, which can be used to define the *submodels.*

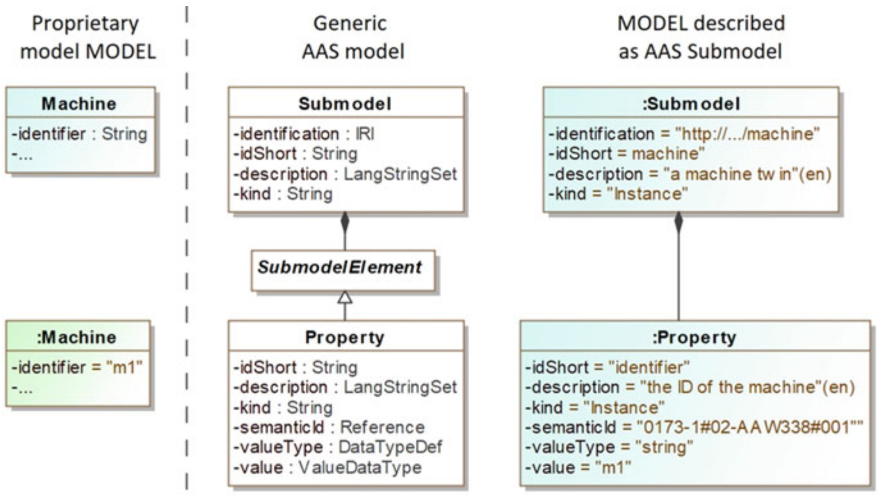


Fig. 10 Simple AAS submodel construction sample

Figure 10 illustrates the principal structure of submodels in the AAS standard and the method of developing an AAS submodel for any model. The left panel displays a simplified proprietary, that is, a nonstandard data model (named *MODEL*) of a machine's DT. Its instantiation is shown below, describing a concrete machine *m1*. Only one attribute is displayed here to focus on the mechanisms of translating this model to an AAS submodel.

The middle panel of Fig. 10 shows the simplified *generic* AAS model. The right panel shows that this model is instantiated to build the given proprietary model. Each submodel has an Internationalized Resource Identifier (IRI) [60], an *idShort* (often being the last part of the IRI), *descriptions* (several pairs of language tags and strings in that language are allowed), and a kind (being *Type* or *Instance*). A submodel is composed of *SubmodelElements*. Different subclasses exist, such as *Property*, *File,* and *Collection* (the latter are not shown).

For all attributes of the given model, an AAS *Property* can be added to the AAS *Submodel*. A *Property* is a name–value pair with additional metadata. Here the semantic annotation using its attribute *semanticId* is crucial for automatic interpretation. In this example, an International Registration Data Identifier to an attribute defined by the eCl@ss [61] standard is used. The eCl@ss dictionary contains properties for product descriptions and service descriptions based on standardized data formats conform to IEC 61360 [62]. Alternatively, an IRI referencing a standard property of well-known ontologies is usable (e.g., https://schema.org/identifier). A third alternative is to use own IEC61360 conformant so-called *ConceptDescriptions*, stored within an AAS.

The last attributes are *valueType* and *value*. A value can only be set if *kind* = *Instance*. This context indicates that types and their instances appear similarly, and only the attribute *kind* and the attribute *value* differ. *DataTypeDef* is any XSD datatype [63], and *ValueDataType* is a value of such type.

Assets may be composed of other assets. In this case, a composite AAS is constructed, which has a bill of material listing its parts. These assets may be co-managed within the comprising AAS, or they may be self-managed, that is, they all have their own AAS. Therefore, complex AAS structures can be built, which may reflect the physical asset structuring.

The data model and the corresponding data can be serialized (i.e. automatically transformed to), for example, as extensible markup language (XML), JavaScript object notation (JSON), resource description framework (RDF), or open platform communications-unified architecture (OPC-UA). The standard also defines all these mappings. An AAS can be entirely transported as a so-called AAS extension (AASX) package. Furthermore, a representational state transfer API (REST-API) of an AAS is currently being defined and specified by PI4.0. It will be defined as part 2 of the AAS specification [59], but is work in progress, and intends to standardize the AAS interfaces.

Another module in the AAS information model is the attribute-based access control (ABAC) based security model, which protects the AAS, e.g. its REST-API. For each subject (role or user), it can be specified which object (submodels or even properties) the user is allowed or denied to read or to modify using expressions over attributes of the subject, the object, and the context.

The AAS specification does not provide methods to describe how a physical asset can be connected with its AAS. Anything is allowed here, hidden to the AAS users. Therefore, the AAS homogenizes the assets' diversity in the real world by providing a standard ecosystem plug.

4.4 Data Sharing Standards

DTs are a mature instrument for data collection and integration that can bridge media disruptions between distributed systems [64]. A DT forms a central knowledge base within a company and contributes to enhance business processes [64]. Although the benefits of DTs are not limited to their use for internal company processes, they are mainly used to monitor the internal processes. In this context, DTs are a suitable instrument for sharing data with various stakeholders [65], which companies find it increasingly important as data represents a strategic resource with economic value [66].

In principle, the difference between exchange and sharing of data must be recognized. Exchange of data occurs only in terms of vertical cooperation between companies, where the optimization of value or supply chains is one of the objectives. This type of data exchange is common and based on standards developed since the introduction of electronic data exchange in the 1980s. Data sharing, however, describes the vertical and horizontal collaboration between companies to achieve common goals; for example, predictive maintenance through collaborative data sharing, in which both the company providing the data and that using it mutually benefit through improved services and databases [59].

The shared DT is necessary for implementing collaborative data sharing. It is based on the fundamental concepts of a general DT, which are characterized by the integration of various data formats from distributed data storage and the description of data with meta-information [67]. Following the definition of data sharing, a shared DT describes the extension of the archetypical characteristic of a DT by the functions of interoperable and sovereign use in collaborative networks. This extension includes the standardized data model, which in turn includes the uniform description of interfaces. The respective data model must enable manufacturer-neutral and cross-company interoperability.

A shared DT is further characterized by the emphasis on security concepts and, in this context, especially the concepts for data policy enforcement. Access control is an essential tool for data policy enforcement for DTs and restricts the access to functionalities and the asset model information of the DT [68]. However, data sovereignty must be considered in the use of DTs in collaborative networks. It is the ability of a natural or legal person to exercise exclusive self-determination over the economic asset data [59] and based on the data policy enforcement on usage control. In contrast to traditional access control, usage control regulates future data usage by adding restrictions [69]. Access control, therefore, manages the rights to collect data, while usage control determines how the recipient can use the data [70, 71].

Within an enterprise, data security, accountability, and transparency are defined. If data leaves the enterprise, additional security is required. For shared DTs, it must be ensured that the company providing the data always retains sovereignty. Therefore, the *International Data Spaces Association* (IDSA) [72] has developed a reference architecture, which enables the secure and sovereign exchange of data between trustworthy parties. It defines a technical infrastructure and a semantic set of rules for data exchange and data usage in ecosystems. DIN SPEC 27070 [73], based on the Industrial Data Spaces (IDS) reference architecture model, is the first global and interoperable standard.

The AAS is a virtual digital and active representation of an asset and renders a standardized I4.0 component in an I4.0 (eco)system composed of such building blocks. For multilateral data exchange, the AAS offers an appropriate basis for interoperability between the actors mentioned earlier through its upcoming standardization. The *Fraunhofer Gesellschaft* is currently working on the combination of IDS and AAS (see Case Studies in Sect. 7). The AAS-REST-API will be realized as an IDS Data App, which can be offered in an IDS App Store if necessary. IDS messages contain AAS-compliant data with IDS references to resources available via IDS. The ABAC of the AAS is synchronized with IDS Contracts and AAS subjects with IDS Participants. The IDS is more focused on communication (data in movement) and provides general interfaces but does not specify payload formats, whereas the AAS standards are more concrete. In complex and automated I4.0 scenarios, new legal issues arise, currently being investigated in the legal testbed project [74] in cooperation with IDSA and PI4.0.

A combination of both concepts, the IDS and the AAS, likely ensures interoperability between various stakeholders and respects individual data protection needs. Both are industry-neutral approaches, also applicable to production systems. Their combination is a reasonable basis for a shared DT. In particular, interoperability in this context refers to the likelihood of simple migration to various cloud and edge providers. The GAIA-X project [75] aims to enable such cross-cloud usage. In general, GAIA-X forms a networked and provider-neutral data infrastructure that enables secure storage (data in rest), sovereign exchange, and collaborative use of data and services.

5 Integration of Models and Data Sources into a DT-Compatible Platform

Integrating different data sources is a major advantage of implementing DTs. For example, a product's DT typically requires information from not only enterprise resource planning (e.g., batch id and recipe), but also process control (e.g., the used amount of supply material and produced product and resource consumption for the product). Data can be integrated by storing information from different sources on a specific platform, such as a cloud as well as an on-premise platform. An example of a cloud-based platform is MindSphere™ [76], which has been used in the EIT Food project "Digital Twin Management" (Sect. 7.1) [77]. The main advantage of using a cloud-based platform is that there is no need for resources to maintain the corresponding IT infrastructure and data backups and that the data is available everywhere. Platforms need to include a user and access management as well as IT security measures for the exchange of information.

A use case specification for a digitalization project may reveal the lack of data and interfaces. This is particularly significant for brownfield installations with low-level automation or connectivity and requires investments in the automation network, additional sensors, and engineering of additional data points. Connecting various data sources with the platform can be supported with suitable devices and software modules. Automation components such as controllers need to connect to the platform, as well as to a REST-API. Software tools require a connection to other sources such as SAP systems.

Once the data is available on a platform, it can be used for visualization and analysis. These apps can be created and provided as a service by any provider. However, data access and analysis are simplified mainly by using a suitable data model, providing a meaningful semantic description of the data on the platform.

DTs can also be used to increase the transparency of value chains. This is achieved by sharing parts of DTs with business partners or authorities. Data ownership must be respected by such a solution, for example, preventing data users from accessing or even manipulating an owner's data without consent. An excellent

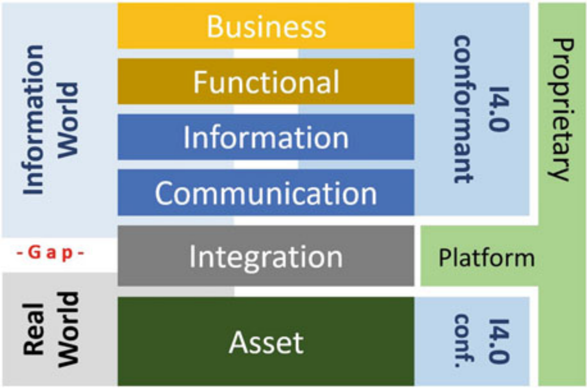


Fig. 11 RAMI 4.0 layers adopted from PI4.0 [79]

introduction to the different roles and some useful rules for data sharing can be found in the EU code of conduct on agriculture data sharing [78].

For successful integration in terms of I4.0, the Reference Architecture Model Industry 4.0 (RAMI 4.0) is a well-established guidance for implementation. It unifies the most relevant aspects of the I4.0 architecture and represents the holistic life cycle of assets. The RAMI 4.0 supports a uniform structure, wording, entire scope of I4.0, and complex relationships in small and clear parts. The RAMI 4.0 model consists of three dimensions: hierarchy, product life cycle, and architecture. Architecture is subdivided into six layers: business, functional, information, communication, integration, and asset. In the information layer, different data models can be integrated (e.g., submodels of asset administration shells), which get their data from the lower levels (i.e., communication or asset), while the functional and business layer provide the processing logic. Applied to bioprocesses, e.g. kinetic models can be integrated with other data sources, and the functional layer can combine them accordingly.

Figure 11 displays the layers of PI4.0 architecture reference model RAMI 4.0, which spans from real world to the information world. Between both worlds, there is a gap in the current PI4.0 standards: The asset layer is the lowest layer in RAMI 4.0 and represents the assets of the physical world, such as a machine in a production environment. The integration layer in RAMI 4.0 acts as a link between the real and the information world and is not yet standardized as the higher layers. This gap can be covered by the assistance of appropriate platforms.

6 Risk and Hurdles for a DTMS Implementation

Prior to the integration of a DTMS into operating plants, some major hurdles and risks must be addressed. Section 3 and 4 explain and discuss several plant adaptations scenarios in which risks could occur. According to Singh et al. [80] depending on the aspect to be considered, the challenges or risks can be classified into several groups: engineering, commercial, technology, and data challenges.

The engineering challenges and risks require standardization and hardware adaption (see Sect. 4). It is necessary that all physical assets communicate with the DTMS in one language. The integration of the DTMS with the automation systems of an existing plant may require additional often unforeseen efforts, in particular if these automation systems involve a proprietary solution or are lacking corresponding interfaces. Increasing the complexity of the systems related to the implementation of a DTMS is also a challenging task. To minimize risks, integration work must start very early, so that problems that could arise can be resolved in time. A detailed work plan must take foreseeable risks into account and provide a suitable buffer in terms of effort and time.

Commercial issues can include data sharing difficulties with the stakeholders that are part of the value chain. On the one hand, it offers a high level of synergy effects and numerous benefits, but on the other hand, information sharing and ownership could raise some challenging technological issues. In this context, Singh et al. [80] mainly addressed company policies, the way of thinking of involved stakeholders, and cultural differences. These difficulties and occurring issues can reduce the effectiveness and overall benefit. Customs control regulations could also cause delays and possibly additional costs in delivering the DTMS to the partners. Having to take into account multiple food safety regulations across the world may exceed not only the available resources for the project but also the complexity of the solution. This can be avoided by focusing on highly relevant market segments and/or regions.

Technology challenges may increase costs and implementation time, e.g. for CPS (cyber-physical system) implementations. An industrial CPS (ICPS) connects the cyber and virtual world. Notably, the life cycle of ICPS components needs to be clarified [81]. Often heterogeneous systems need to be integrated using different technologies; they implement different standards or even have proprietary interfaces. Moreover, communication or computation bottlenecks may occur when vast amounts of data are collected from the automation systems. The technical requirements of the new primary framework for the DTMS require detailed planning.

A more fundamental challenge in the DTMS implementation is the data itself. This requires intensive support through the highly complex and external communication across process and company borders. Secure system integration is a challenge for any company, especially when interfacing other companies' systems. Untrusted interfaced systems outside the company are a security risk. All information exchange should follow the common policies and possible threats have to be considered. The information flow should be controlled to limit attack vectors like identity thefts or privacy and security breaches. Information should also be validated and filtered. A standardization of the system integration process based on the definition of security requirements helps reduce these risks.

Internal data security must be redesigned based on these new demands. The existing systems must be adapted to upcoming or future requirements and to new security issues [82]. Data access control and even data usage control may be required when data sovereignty needs to be enforced. It needs to be supported appropriately by all involved systems. Moreover, the resulting new high-level of networking poses a particular risk. Data loss can range from image damage to loss of company trade

Table 1 Selected examples of risks, hurdles, and corresponding solutions

Step	Hurdles/current state	Consequence/solutions
Stakeholders analysis	Internal/external stakeholders; security risks by external stakeholders	Face-2-face interviews, surveys, workshops with design thinking, and creativity sessions
Use case specification	Analyze current and future business impact for use cases, prioritize them, define data and workflow including all relevant components, both for current and for desired situation	Interviews and workshops, qualitative description and evaluation of strategic business impact, SWOT, scoring methods, AHP, business process model and notation (BPMN), UML
Infrastructure analysis	Define minimum sensor, operational, and transactional data in sufficient granularity and define enabler technologies for physical system integration	Select integration technology, e.g. AAS, IDS, MindSphere
Process characterization	Analyze all physical production equipment and procedures, categorize them by Fig. 7, e.g. batch, continuous, and discrete.	How to support manual tasks by HMIs How to analyze the data (e.g., use of AI)
Composition of big picture	Integrated complete high-level vision of the “To-Be” system, depicting future operation	Abstraction, considers, e.g., current trends, social and economic perspective and own objectives
Process standardization	Many process standards, modeling detail	Select one, e.g. BPMN, structured according to ISA-88
Data standardization	Many data standards, modeling detail	Select one, e.g. UML, structured according to PI4.0 AAS, serialized as XML or JSON
Data sharing standardization	Data exchange or collaborative data sharing, access control and usage control	DIN SPEC 27070, ABAC, IDS Usage Control

secrets or intellectual property. This can be a challenging step, due to unclear internal and external communication channels at the beginning of the planning process. In the planning phase, all potential weak points need to be considered.

Further data challenges include concepts like data acquisition, type, transfer points, streams, database handling, big data storing, and data security. One potential risk is that the data collected from plants or products are not adequately representing the same concept. This can lead to, e.g., information available in digital twins being incomplete or not up-to-date, and not being sufficient for, e.g., getting reliable results from a root cause analysis. One possible solution is an overview of the treatment of food safety issues, which helps identify relevant information, and allows for early measures to provide this information, e.g., by installing new sensors and capturing new relevant data. By early and detailed planning, this risk can be reduced. Especially these points show the challenges of a DTMS implementation. Nevertheless, they are not unknown problems, and therefore they can be minimized by proper and detailed planning in advance (Table 1).

7 Case Studies

This section presents three case studies for implementing DTs in operating production lines or entire value chains. The work was carried out in different research projects in which the authors were actively involved.

7.1 Digital Twin Management: Implementation of a DTMS in an Operating Production Process

The first case study originates from the EIT Food project "Digital Twin Management" (DTM, 2018–2019) and was adapted from previous works [77, 83]. A DT structure and a DTMS were implemented into the value chain of pudding production, including the production of the required flavors. Thus, two different companies and corresponding plants required a suitable connection within the DTMS. The recipe for the pudding product included skimmed milk, flavors, sugar, fat, and other ingredients. A producer of flavors manufactured the flavor ingredients and a dairy plant was responsible for the actual pudding production. Figure 12 illustrates the corresponding big picture, which includes the physical model and the data model. Internally, in both companies, quality managers, warehouse managers, and production managers aimed to participate in the DTMS. In addition to the two companies, the stakeholder analysis identified three other major parties: authorities, customers, and logistics. Notably, the authorities and customers benefit from the DTMS via apps delivering suitable production data.

Process and structural characterization were first realized for the producer of flavors. Moreover, an MES and data storage system existed in the process line. The process type was batch related and comprised three different process sections: warehouse, production, and storage. Each production step represents an individual unit operation: juicing, filtering, and rectifying. According to the standards explained in Sect. 4, they are declarable as units. In addition, various sensors that measure temperature, pressure, and weight were identifiable. The system also registered timestamps of several process starts and ends and was confirmed via HMIs. These data points were declared as control modules according to the selected standards. Manual transport helped connect between the units, and timestamps registered the layover of a batch at a particular unit.

The dairy plant was also batch related and was equipped with various management systems (MES, LIMS), historical data storage, and partially automated production facilities. Five different process sections existed: warehouse, milk storage, pudding production, cream production, and packaging. Pudding production was targeted for the DT implementation. This process includes four steps: ingredient mixing, homogenization, pasteurization, and packaging. The cream production consists of fat storage, cream whipping, and cream storage. Both process sections include various physical assets such as sensors (e.g., temperature, pressure, and pH)

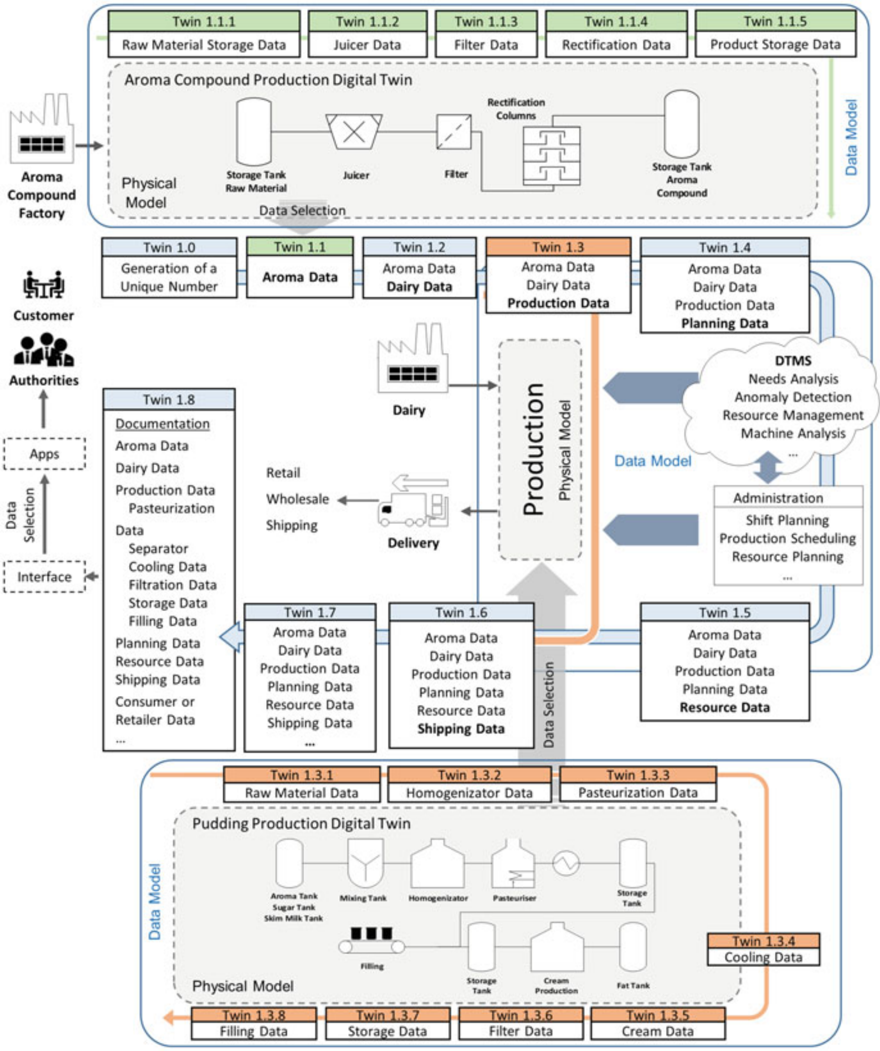


Fig. 12 Big picture of the DT implementation in the supply chain of dairy production (adopted from [77])

and actuators (e.g., motors and valves). The valves connected the individual sections defining timestamps for the product section transfer. Furthermore, some extensions could connect incompatible and non-standardized machines and sensors to the DTMS. HMIs were also considered with a comprehensive documentation option and included in the DTMS.

Two physical models were derived from the analysis of the companies and processes. Given that the project aimed at tracking and tracing, only the equipment and components with direct product contact were considered. Following further analysis of the sensory and the structural conditions (especially IT-related structures), the two corresponding data models with all relevant data points for the DTMS were created. These virtual models also comprise the actual DTs and their data. In terms of the physical model, the DTs are classified in the correct production order and with a suitable semantic designation. Owing to the progress in the production within the value chain, the DT is continuously growing in terms of data equipment, as new, relevant data points are added in each further process step related to the physical model. Hence, the first DT in the value chain is the data poorest, while the last DT receives the most and all relevant data points. Subsequently, all the models were connected via appropriate interfaces and the respective analyzed stakeholders were involved. The overall structure of all the components finally results in the big picture, which shows the DTMS, the structure of the DTs, and the stakeholders involved (Fig. 12). The big picture results in individual structures for each value chain and must always be created anew. Furthermore, it provides a complete overview of the architecture of the DTMS and apps for the stakeholders. It is the crucial step in the implementation of a DTMS and has a considerable impact on its functionality.

In this case study, DTs aimed to ensure full traceability and trackability along the value chain. Besides, the connectivity between the companies, plants, production areas, and process cells was reached. These measures support the use of PI4.0 potentials and the stakeholder participation. The connection of both companies considered by the full big picture creates one DTMS that enables the complete reconstruction of the processes.

7.2 *Organic Supply Chains: Implementation of a DTMS for Vegetable and Beef Supply Chains*

The approach of the DTM project (Sect. 7.1) is also used and extended in the EIT Food project “Organic Supply Chains” (OSC, 2019, ongoing) [84], which builds a MindSphere™ DTMS for vegetable and beef supply chains. The main objective is to prove the organic status and safety of the produced food. The supply chains extend from ordering and planning over processing to delivering to retailers. They connect farmers, food producers, transporters, and retailers. Figure 13 presents an overview of such a supply chain.

In the DTM project, all involved companies were project partners. Thus, all data points and systems were accessible by them, and the complete production process could be covered. In contrast, in the OSC project, only the retailers are currently the project members, resulting in limited data and source system access. In the OSC project, there is no concrete physical model of the farms with detailed specifications of work centers and units for which DTs are requested. Instead, complex business process models and notation models are used to define all the process steps. The

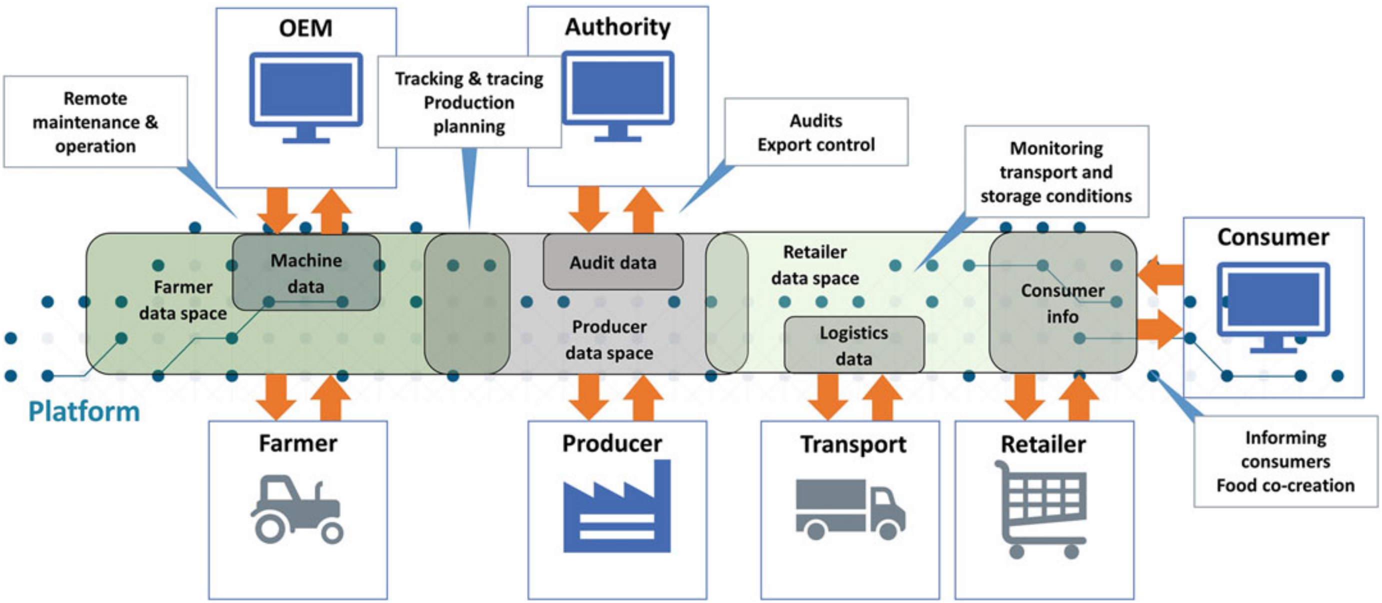


Fig. 13 Sharing digital twin data with stakeholders in an agri-food value chain enables many use cases

relevant activities/work units and even the work centers were identified following ISA-88. Organic supply chains have strong linkages and communication between the process participants and the majority of the steps are manual. Moreover, the data is complex, and the processes involve various communicating partners. Therefore, detailed UML models are used in the OSC project and structured according to ISA-88 hierarchies.

7.3 Shared Digital Twins

The Fraunhofer cluster of excellence "Cluster of Cognitive Internet Technologies (CCIT)" [85] studies cognitive technologies for the industrial internet. Researchers from multiple disciplines are developing key technologies for various levels along the value chain, from sensors and intelligent learning methods for data processing up to cloud technologies. Its *Forschungszentrum Data Spaces* (FDS) focuses on concepts and technologies for sovereign industrial data exchange based on the IDS. An integral aspect of the FDS is the cross-institutional cooperation between numerous Fraunhofer Institutes collaborating on projects. One of these projects relates to the integration of IDS Connectors and AAS and, accordingly, with the combination of the information models and the security concepts of both approaches. It aims to develop a shared DT based on the current and future standards for interoperability and data sovereignty.

RIOTANA® (Realtime IoT Analytics) is a domain-independent IoT architecture and DT that processes raw sensor data into key process indicators (KPIs) in real-time, developed by Fraunhofer ISST [86]. It consists of sensor modules attached to arbitrary assets (e.g., forklifts), which transmit their data via Message Queuing Telemetry Transport (MQTT) to a backend, which can combine the sensor values and calculate KPIs. The combination of a proprietary DT such as RIOTANA® with IDS and AAS leads to a shared DT complying with the corresponding standards. The data can be accessed by multiple participants in the ecosystem, while the data owner retains full control over the data. The owner can define who can access and use the data and for what purposes the data can be used. By using IDS, its usage control mechanisms can be applied.

Figure 14 shows the architecture of the combination: on the right panel, as sample assets, three forklifts *f1–f3* are shown with attached RIOTANA® sensor modules, which transmit their values to the RIOTANA® DT. The latter is now an IDS data app in a service container and used to implement the standard AAS-REST-API, which also is an IDS data app acting as the AAS wrapper for RIOTANA®. In this case study, there is a composite forklift fleet asset with co-managed forklift assets.

The combination of AAS and IDS results in an architecture that requires the mapping of the data models and security concepts: IDS messages contain AAS-compliant data with references to IDS resources. The AAS-ABAC security concept is combined with IDS contracts, which protect those resources. The submodels of the AAS are protected by both mechanisms and may be subject to

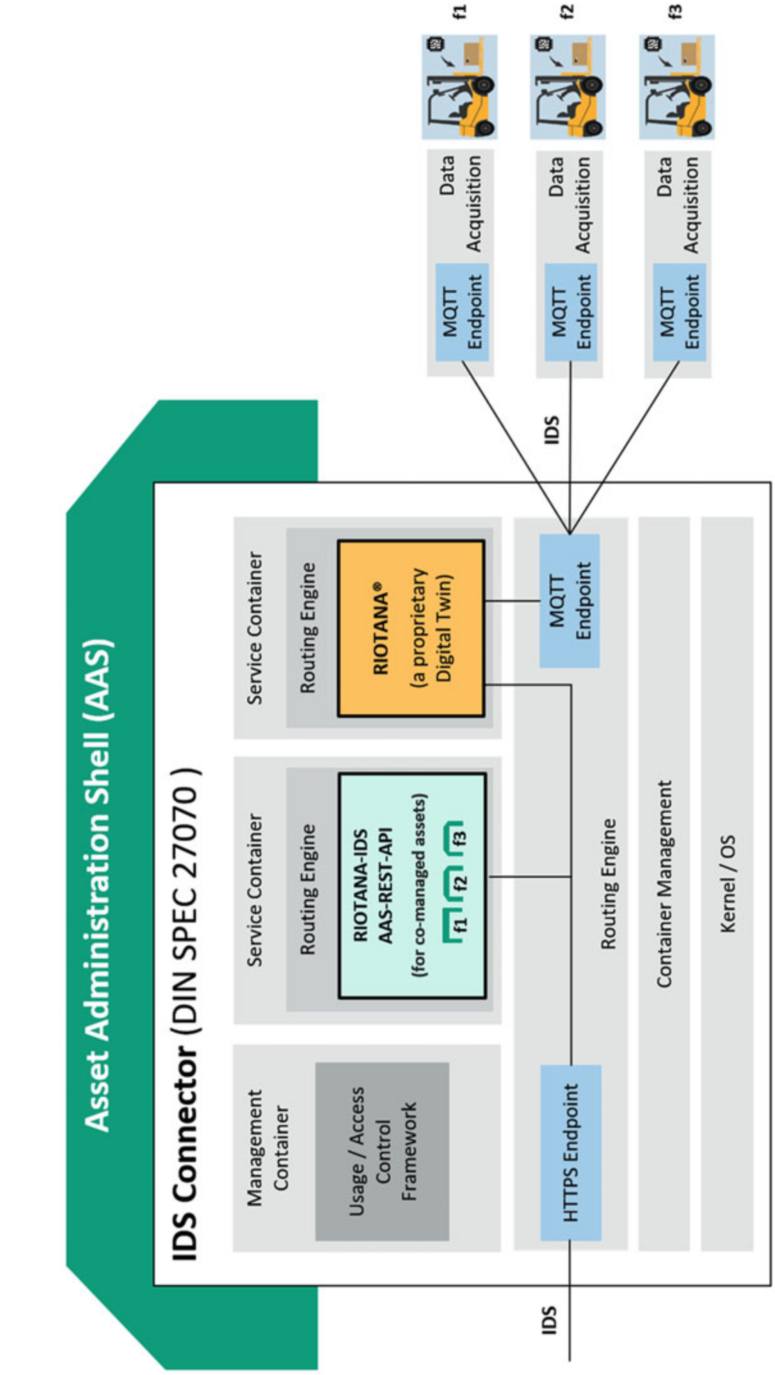


Fig. 14 Architecture of the RIOTANA-IDS-AAS

IDS usage control. This approach is independent of RIOTANA®; it can be used to convert any proprietary DT into a standard (AAS) sovereign (IDS) sharable DT by providing an IDS-AAS wrapper. This also holds for proprietary DTs of production processes and their parts and products. The use of established concepts and approaches for interoperability and data security is, therefore, the basis for the design of shared DTs.

8 Summary and Outlook

In I4.0, new types of cooperation have replaced rigid value chains. The boundaries between country, industry, and company are being blurred. Plants, machines, and products communicate autonomously in digital, globally connected networks. Therefore, dynamic and self-optimizing ecosystems will emerge, which comprise several decentralized stakeholders. In digital ecosystems, all relevant physical assets must be integrated into the I4.0 environments to interact with each other. Everything is mapped digitally and uniformly, ensuring transparency along the entire value chain. Moreover, there are no instances of central control, but several decentralized combined "building blocks." In an open ecosystem, no stakeholder may assume a monopolistic position. The core elements are DTs. There are various solutions: exemplary platforms provide extensive solutions for integrating asset data into DTs, ranging from hardware to software, but the solution is proprietary. On the other hand, standardization approaches, such as the AAS, a key concept of the German PI4.0, exist. It, however, does not provide or standardize any means to connect the asset to the AAS and hence any mechanism can be used.

DTs and DTMS generate voluminous amounts of valuable data accessible and processable, which enable several novel applications. The concept of DTs helps determine the current state of a product along the entire product life cycle. Therefore, the design of the DT must provide the communication between the DTs and with complex architecture (e.g., management, administration, and planning services). Individual machines or entire production lines are also represented by distinct DTs (e.g., in the form of an AAS). However, the abundance of data often requires a strict definition of system boundaries or requires data usage control in the global digital ecosystem.

In bioprocesses and related industries, DTs enable a full digitalization with all associated concepts and tools. Not only complete monitoring of the whole value chain becomes possible but also tracking and tracing of the individual steps/units. Bioprocess unit operations are concludable in distinct DTs, which allows optimization, automated process monitoring as well as intelligent control and process state prediction (e.g., early-warning system). In the future, even automated process as well as product validation are feasible with the support of a comprehensive DTMS. Especially, the resulting increased density of information related to the individual assignments to DTs offers the company new possibilities for product and process monitoring, to increase the scope of networking, and for integrating measuring points that previously had no real-time process connection. Using DTs and the associated peripherals, all relevant information in the value chain, from raw material producer over the bioproduct manufacturer (e.g., food or pharmaceutics) to consumer, can be digitized. Concepts and strategies can be incorporated in the decision-making and quality assurance of bioprocesses.

Approaches from the field of artificial intelligence are a sophisticated method to structure and evaluate the copious data. Sharing information from DTs supplements the DTs with information from other DTs in the B2B sector. Intelligent algorithms can use the information gained from the data for production planning and control. The combination of established simulation and optimization methods as well as the methods from the field of artificial intelligence and machine learning represents a future-oriented technology. Besides, by processing data, KPIs, or forecasts and events information may be included in the optimal configuration of system parameters. Therefore, predictions or behavioral analysis can be applied, and in some cases, repairs of equipment (e.g., fermenters, pumps) can be ordered before the downtime occurs. The digital strategy *Predictive Maintenance* reduces downtimes and associated costs [87, 88]. These predictions are also applicable to resources. Thus, detailed planning of raw material orders can be conducted, or energy can be smartly distributed within the company or, if necessary, diverted to the respective consumer. Furthermore, a detailed production layout planning can be implemented with the help of DTs, where all process resources are used in a time-optimized manner [89]. Hygiene concepts, hygiene state of the equipment, and the hygienic monitoring of associated cleaning concepts can be monitored by DTMS. Moreover, structured DTs in a DTMS help distribute the planning between production units and production systems, improved decision support by simulation models, production unit planning, and automated execution of offers and orders [4].

The comprehensive data collected and evaluated supports documentation of the entire life cycle. This aspect enables higher traceability and new analyses on quality assurance. In particular, the cross-linking, distant from rigid linear hierarchies, creates higher transparency and, thus, new approaches to monitor and analyze processes. A holistic view of the production and the company leads to new means and methods of standardization, which lead to higher efficiency. Plant or product data can be processed directly in the cloud and provided in real-time, and any deviations are detected swiftly. Accordingly, one of the main challenges is to find the root cause of the event within an acceptable time frame and without much effort. Here, machine learning-based anomaly detection can be used. This approach does not directly lead to a root cause but helps identify conspicuous time ranges and production batches. The DTMS and cloud platforms enable patterns to be recognized through various evaluation algorithms and, thus, processes and products can be evaluated in detail and autonomously.

References

1. Forschungsunion, Acatech (2013) Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Final report of the Industrie 4.0 Working Group. https://www.din.de/blob/76902/e8cac883f42bf28536e7e8165993f1fd/recommendations-for-implementing-industry-4-0-data.pdf. Accessed 3 Jun 2020
2. Negri E, Fumagalli L, Macchi M (2017) A review of the roles of digital twin in CPS-based production systems. Procedia Manuf 11:939–948. https://doi.org/10.1016/j.promfg.2017.07.198
3. Kritzinger W, Karner M, Traar G et al (2018) Digital twin in manufacturing: a categorical literature review and classification. IFAC-PapersOnLine 51:1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474
4. Rosen R, von Wichert G, Lo G et al (2015) About the importance of autonomy and digital twins for the future of manufacturing. IFAC-PapersOnLine 48:567–572. https://doi.org/10.1016/j.ifacol.2015.06.141
5. Liu S (2013) Bioprocess engineering: kinetics, biosystems, sustainability, and reactor design, 1st edn. Elsevier, Amsterdam
6. Taylor DH (2005) Value chain analysis: an approach to supply chain improvement in agri-food chains. Int J Phys Distrib Logist Manag 35:744–761. https://doi.org/10.1108/09600030510634599
7. Fearne A, Garcia Martinez M, Dent B (2012) Dimensions of sustainable value chains: implications for value chain analysis. Supply Chain Manag 17:575–581. https://doi.org/10.1108/13598541211269193
8. Barrientos S (2001) Gender, flexibility and global value chains. IDS Bull 32:83–93. https://doi.org/10.1111/j.1759-5436.2001.mp32003009.x
9. Alfaro L, Antràs P, Chor D et al (2019) Internalizing global value chains: a firm-level analysis. J Polit Econ 127:508–559. https://doi.org/10.1086/700935
10. Trienekens JH (2011) Agricultural value chains in developing countries a framework for analysis. Int Food Agribusiness Manag Rev 14:51–82. https://doi.org/10.22004/ag.econ.103987
11. Bittner K, Spence I (2002) Use case modeling. Safari books online. Addison-Wesley; safari books online, Boston, MA, Sebastopol, CA
12. Nebut C, Fleurey F, Le Traon Y et al (2006) Automatic test generation: a use case driven approach. IIEEE Trans Software Eng 32:140–155. https://doi.org/10.1109/TSE.2006.22
13. Marsch P, Da Silva I, Bulakci O et al (2016) 5G radio access network architecture: design guidelines and key considerations. IEEE Commun Mag 54:24–32. https://doi.org/10.1109/MCOM.2016.1600147CM
14. Ma X, Tao F, Zhang M et al (2019) Digital twin enhanced human-machine interaction in product lifecycle. Procedia CIRP 83:789–793. https://doi.org/10.1016/j.procir.2019.04.330
15. Siepmann D, Graef N (2016) Industrie 4.0 – Grundlagen und Gesamtzusammenhang. In: Roth A (ed) Einführung und Umsetzung von Industrie 4.0: Grundlagen, Vorgehensmodell und Use Cases aus der Praxis. Springer, Berlin, Heidelberg, pp 17–82
16. Deutsches Institut für Normung e.V. (2014) Integration von Unternehmensführungs- und Leitsystemen – Teil 1: Modelle und Terminologie(62264–1:2013)
17. Redelinghuys A, Basson A, Kruger K (2019) A six-layer digital twin architecture for a manufacturing cell. In: Borangiu T, Trentesaux D, Thomas A et al (eds) Service orientation in Holonic and multi-agent manufacturing, vol 803. Springer, Cham, pp 412–423
18. Guo N, Jia C (2017) Interpretation of cyber-physical systems whitepaper (2017). Inform Tech Stand 4:36–47
19. Ibarz A, Barbosa-Cánovas GV (2003) Unit operations in food engineering. Food preservation technology series. CRC Press, Boca Raton
20. Foust AS (1960, reprinted, with corrections, 1962) Principles of unit operations. Wiley, New York

21. International Society of Automation (2010) Batch control part 1: models and terminology (88.00.01-2010)
22. Weyer S, Schmitt M, Ohmer M et al (2015) Towards industry 4.0 – standardization as the crucial challenge for highly modular, multi-vendor production systems. IFAC-PapersOnLine 48:579–584. https://doi.org/10.1016/j.ifacol.2015.06.143
23. Hallscheidt S, Adomeit N, Manske T et al (2019) 1x1 der Normung: Ein praxisorientierter Leitfaden für KMU. https://www.din.de/resource/blob/69886/5bd30d4f89c483b829994f52f57d8ac2/kleines-1x1-der-normung-neu-data.pdf. Accessed 3 Jun 2020
24. Lu Y, Liu C, Wang KI-K et al (2020) Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues. Robot Comput Integr Manuf 61:101837. https://doi.org/10.1016/j.rcim.2019.101837
25. Deutsches Institut für Normung e.V. Normung auf einen Blick. https://www.din.de/resource/blob/249724/2dcba02aa757691193e37aa80a1a6e17/infografik-normung-auf-einen-blick-data.pdf. Accessed 31 Mar 2020 at 07:48pm
26. International Organization for Standardization (under development) Digital twin manufacturing framework: part 1: overview and general principles (23247-1)
27. International Organization for Standardization (under development) Digital twin manufacturing framework: part 2: reference architecture (23247-2)
28. International Organization for Standardization (under development) Digital twin manufacturing framework: part 3: digital representation of physical manufacturing elements (23247-3)
29. International Organization for Standardization (under development) Digital twin manufacturing framework: part 4: information exchange (23247-4)
30. International Organization for Standardization (under development) Automation systems and integration — industrial data: visualization elements of digital twins (24464)
31. International Society of Automation (2001) Batch control part 2: data structures and guidelines for languages (88.00.02-2001)
32. International Society of Automation (2003) Batch control part 3: general and site recipe models and representation (88.00.03-2003)
33. International Society of Automation (2006) Batch control part 4: batch production records (88.00.04-2006)
34. International Society of Automation (2010) Enterprise-control system integration: part 1: models and terminology (95.00.01-2010 (IEC 62264-1 Mod))
35. International Society of Automation (2018) Enterprise-control system integration: part 2: objects and attributes for enterprise-control system integration (95.00.02-2018)
36. International Society of Automation (2013) Enterprise-control system integration: part 3: activity models of manufacturing operations management (95.00.03-2013)
37. International Society of Automation (2018) Enterprise-control system integration: part 4: objects and attributes for manufacturing operations management integration (95.00.04-2018)
38. International Society of Automation (2018) Enterprise-control system integration: part 5: business-to-manufacturing transactions (95.00.05-2018)
39. International Society of Automation. Enterprise-control system integration: part 6: messaging service model (95.00.06-2014)
40. International Society of Automation (2017) Enterprise-control system integration: part 7: alias service model (95.00.07-2017)
41. International Society of Automation (2015) Machine and Unit States: an implementation example of ANSI/ISA-88.00.01(TR88.00.02-2015)
42. International Society of Automation. Procedure automation for continuous process operations: models and terminology (106.00.01)
43. International Society of Automation (2017) Procedure automation for continuous process operations: work processes (106.00.02-2017)
44. International Society of Automation (2008) Using ISA-88 and ISA-95 together (88.95.01-2008)

45. International Society of Automation. Enterprise-control system integration: TR01: master data profile template (95.01-2018)
46. International Society of Automation (2015) Human machine interfaces for process automation systems (101.01-2015)
47. ZVEI – Zentralverband Elektrotechnik- und Elektronikindustrie e. V. (2015) Modulbasierte Produktion in der Prozessindustrie – Auswirkungen auf die Automation im Umfeld von Industrie 4.0: Empfehlungen des AK Modulare Automation zur NE 148 der Namur, Frankfurt am Main
48. International Organization for Standardization (2015) Quality management systems: requirements (9001:2015)
49. International Organization for Standardization (2018) Energy management systems: requirements with guidance for use (50001:2018)
50. International Organization for Standardization (2018) Occupational health and safety management systems: requirements with guidance for use (45001:2018)
51. International Organization for Standardization (2018) Food safety management (22000:2018)
52. International Organization for Standardization (2013) Food safety management systems: requirements for bodies providing audit and certification of food safety management systems (22003:2013)
53. International Organization for Standardization (2007) Traceability in the feed and food chain: general principles and basic requirements for system design and implementation (22005:2007)
54. Deutsches Institut für Normung e.V. (2000) Chargenorientierte Fahrweise: Teil 1: Modelle und Terminologie (61512)
55. International Electrotechnical Commission (1997) Batch control: part 1: models and terminology (61512-1:1997)
56. International Society of Automation (1996) Possible recipe procedure presentation formats (88.0.03-1996)
57. Heidel R, Hoffmeister M, Hankel M et al (2017) Industrie4.0 Basiswissen RAMI4.0: Referenzarchitekturmodell mit Industrie4.0-Komponente, 1st edn. VDE Verlag GmbH; Beuth Verlag GmbH, Berlin, Wien, Zürich
58. Affairs and Energy, Federal Ministry for Economics (2020) Project GAIA-X. https://www.bmwi.de/Redaktion/EN/Publikationen/Digitale-Welt/project-gaia-x.html. Accessed 21 Apr 2020
59. Otto B, Steinbuß S, Teuscher A, Lohmann S (2019) Reference architekture model 2019: version 3.0. https://www.internationaldataspaces.org/wp-content/uploads/2019/03/IDS-Reference-Architecture-Model-3.0.pdf. Accessed 30 Mar 2020
60. Tools.ietf.org, Rfcmarkup Version 1.129d On (2020) RFC 3987 – Internationalized Resource Identifiers (IRIs). https://tools.ietf.org/html/rfc3987. Accessed 21 Apr 2020
61. (2020) eCl@ss: home. https://www.eclass.eu/en/index.html. Accessed 21 Apr 2020
62. International Electrotechnical Commission (2017) Standard data element types with associated classification scheme: part 1: definitions – principles and methods (61360-1:2017)
63. The World Wide Web Consortium (2018) XML schema part 2: datatypes second edition. https://www.w3.org/TR/xmlschema-2/. Accessed 21 Apr 2020
64. Wang XV, Wang L (2019) Digital twin-based WEEE recycling, recovery and remanufacturing in the background of industry 4.0. Int J Prod Res 57:3892–3902. https://doi.org/10.1080/00207543.2018.1497819
65. Wagner C, Grothoff J, Epple U et al (2017) The role of the industry 4.0 asset administration shell and the digital twin during the life cycle of a plant: September 12–15, 2017, Limassol, Cyprus: 1–8. https://doi.org/10.1109/ETFA.2017.8247583
66. Otto B, ten Homplel M, Wrobel S (2018) Industrial Data Spaces: Referenzarchitektur für die Digitalisierung der Wirtschaft. In: Neugebauer R (ed) Digitalisierung: Schlüsseltechnologien für Wirtschaft und Gesellschaft, 1st edn. Springer, Berlin, pp 113–133
67. Capiello C, Gal A, Jarke M et al (2020) Data ecosystems: sovereign data exchange among organizations (Dagstuhl Seminar 19391). https://doi.org/10.4230/DAGREP.9.9.66

68. Steinmetz C, Rettberg A, Ribeiro FGC et al (2018) Internet of things ontology for digital twin in cyber physical systems. In: SBESC 2018: 2018 VIII Brazilian symposium on computing systems engineering: proceedings: Salvador, Brazil, 6–9 November 2018. Conference Publishing Services, IEEE Computer Society, Los Alamitos, CA, pp 154–159
69. Jung C, Eitel A, Schwarz R (2014) Enhancing cloud security with context-aware usage control policies. In: Plödereder E, Grunske L, Schneider E et al (eds) Informatik 2014: Big Data – Komplexität meistern: 22–26 September 2014, Stuttgart: proceedings. Gesellschaft für Informatik, Bonn, pp 211–222
70. Bussard L, Neven G, Preiss F-S (2010) Downstream usage control. In: IEEE international symposium on policies for distributed systems and networks (POLICY), 2010: 21–23 July 2010, Fairfax, Virginia, USA; proceedings. IEEE, Piscataway, NJ, pp 22–29
71. Zrenner J, Möller FO, Jung C et al (2019) Usage control architecture options for data sovereignty in business ecosystems. J Enterprise Inform Manag 32:477–495. https://doi.org/10.1108/JEIM-03-2018-0058
72. International Data Spaces e.V. https://www.internationaldataspaces.org. Accessed 23 Jun 2020
73. (2020) DIN SPEC 27070:2020-03, Anforderungen und Referenzarchitektur eines Security Gateways zum Austausch von Industriedaten und Diensten. https://doi.org/10.31030/3139499
74. (2020) Home|Industrie 4.0 Recht-Testbed. https://legaltestbed.org/en/start/. Accessed 21 Apr 2020
75. unn | UNITED NEWS NETWORK GmbH (2020) Die Bedeutung von IDS für die Europäische Digital-Wirtschaft. https://www.pressebox.de/pressemitteilung/industrial-data-space-e-v/Die-Bedeutung-von-IDS-fuer-die-Europaeische-Digital-Wirtschaft/boxid/993608. Accessed 21 Apr 2020
76. Siemens AG (2020) MindSphere. https://siemens.mindsphere.io. Accessed 28 May 2020
77. Werner R, Beugholt A, Takacs R, Geier D, Becker T, Sollacher R, Mauermann M, Weißenberg N, Roest M, Istaitih J (2020) Standardized digitalization of an existing pudding production by introducing a digital twin management system. International Dairy Magazine
78. Copa Cogeca, CEMA, Fertilizers Europe et al (2018) EU code of conduct on agriculture data sharing: Guidelines for correct use of agriculture data. http://www.fao.org/family-farming/detail/en/c/1127623/. Accessed 28 May 2020
79. Tebbje S, Karthikeyan G, Friesen M et al Entwicklung einer IT-Sicherheitsinfrastruktur für verteilte Automatisierungssysteme: Schlussbericht zu IGF-Vorhaben Nr. 19117 N. https://serwiss.bib.hs-hannover.de/frontdoor/deliver/index/docId/1626/file/Schlussbericht_V31.pdf. Accessed 27 May 2020
80. Singh S, Shehab E, Higgins N et al (2018) Challenges of digital twin in high value manufacturing. In: SAE technical paper series. SAE International400 commonwealth drive, Warrendale, PA, USA
81. Colombo AW, Karnouskos S, Kaynak O et al (2017) Industrial cyberphysical systems: a backbone of the fourth industrial revolution. EEE Ind Electron Mag 11:6–16. https://doi.org/10.1109/MIE.2017.2648857
82. Biffl S, Eckhart M, Lüder A et al (2019) Security and quality in cyber-physical systems engineering: with forewords by Robert M. Lee and Tom Gilb, 1st edn. Springer, Cham
83. Werner R, Beugholt B, Takacs R et al (2020) Digitalisierung einer bestehenden Puddingproduktion – Implementierung eines Managementsystems für digitale Zwillinge. molkerei-industrie: 24–28
84. EIT Food (2020) https://www.eitfood.eu/innovation/projects/the-development-of-organic-supply-chains-that-drive-fair-transparent-and-healthy-options-for-the-consumer-2020. Accessed 21 Apr 2020
85. Über den CCIT (2020) https://www.cit.fraunhofer.de/de/ueber-ccit.html. Accessed 21 Apr 2020
86. Haße H, Li B, Weißenberg N et al (2019) Digital twin for real-time data processing in logistics. Proceedings of the Hamburg international conference of logistics (HICL). https://doi.org/10.15480/882.2462

87. Susto GA, Schirru A, Pampuri S et al (2015) Machine learning for predictive maintenance: a multiple classifier approach. IEEE Trans Ind Inf 11:812–820. https://doi.org/10.1109/TII.2014.2349359
88. Rajesh PK, Manikandan N, Ramshankar CS et al (2019) Digital twin of an automotive brake pad for predictive maintenance. Procedia Comput Sci 165:18–24. https://doi.org/10.1016/j.procs.2020.01.061
89. Uhlemann TH-J, Lehmann C, Steinhilper R (2017) The digital twin: realizing the cyber-physical production system for industry 4.0. Procedia CIRP 61:335–340. https://doi.org/10.1016/j.procir.2016.11.152