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Review

Overview of Technology and Functionality Standards for Industry 4.0 and Digitalization in Mechanical Engineering

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Abstract: This paper concerns the identification of current communication technologies and software functionalities from the field of digitalization and Industry 4.0, from the point of view of benefits and applicability for the machine manufacturer. To identify the relevant technologies and functionalities, research was carried out in both the descriptive and statistical literature. As a result, both technologies that are currently the most widely distributed, as well as eleven IT functionalities relevant to mechanical engineers, were identified and described in terms of their application and implementation. Furthermore, a knowledge gap was identified in the area of industry transfer in the field of Industry 4.0/digitalization.

Keywords: Industry 4.0; digitalization; IoT; IIoT; machine; mechanical engineering; software application

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1. Introduction

At the Hannover Messe in 2015, Joe Kaeser, Chief Executive Officer of Siemens, made the following much-quoted statement:

> *"Industry 4.0 is a revolution that will define the 2020s. It will change entire business models and industry worldwide"*

This was more than seven years ago. In the meantime, there has been a large selection of books and publications on the topic of Industry 4.0 and the international term Internet of Things (IoT). These mainly deal with generalist or strategic use and focus on the business model or the effects of the change brought about by Industry 4.0 on these; see Figure 1.

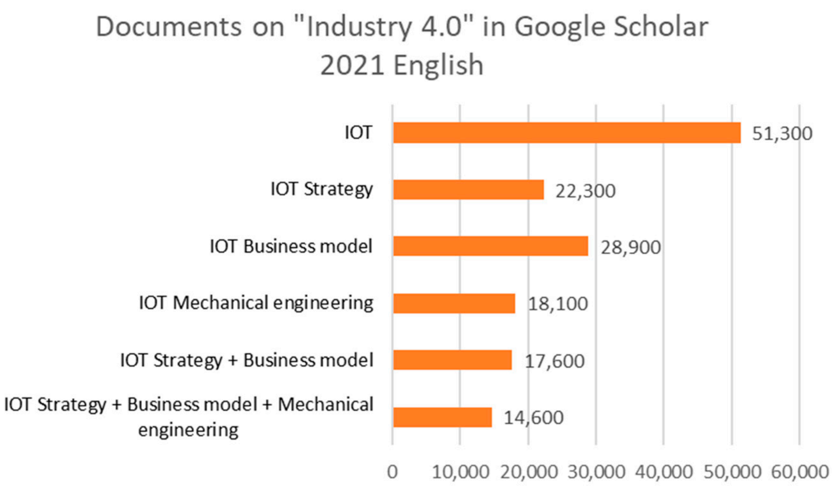

Figure 1. Documents in Google Scholar (publication period: January 2021 to March 2022).

The machine or mechanical engineering itself, as the centerpiece and data supplier, is given little attention in publications on Industry 4.0 or is treated as a subordinate criterion [1–3]. One reason for this is the far-reaching approach to the topic of the IoT or Industry 4.0 [4,5]. In the studies published on this topic, mechanical engineering is viewed as a homogeneous unit in which, for example, construction machinery is treated in the same way as precision machinery [6,7] or no differentiation is made between mechanical engineering companies in a corporate environment and small and medium-sized enterprises (SMEs) [8]. However, this rough generalization does not allow sufficient conclusions to be drawn about the true situation in the mechanical engineering sector.

The aim of this paper is to identify the technologies and functions of digitalization in the transition to the Industry 4.0 environment based on the existing literature. The main focus of this thesis is on machines and mechanical engineering as an independent party. Both the third and fourth industrial revolutions are considered, as these partially overlap. Due to the focus on machines and mechanical engineering and the long amortization periods in this area, the technological standard is regarded as given and reproduced here, while the requirements for functionalities, in relation to technological standards, are regarded as undefined and the research basis and dissemination are progressing rapidly.

Finally, the database for dissemination will be analyzed with regard to the identified functionalities in order to make a well-founded statement about where we stand in relation to Mr. Kaeser's prediction in terms of implementation in practice and knowledge about implementation in practice.

2. Digitalization and Industry 4.0

In the following, the concepts of digitalization and Industry 4.0 are explained for a better understanding as well as how they interlock.

The term digitalization, particularly in the industrial environment, is defined by two aspects: the transfer of analogue available information into a digital form, as well as its storage forwarding, and the use of this very information to generate greater benefits by means of software applications [9,10].

"Industry 4.0 refers to the intelligent networking of machines and processes industry with the help of information and communication technology" [11]; this was adopted as a term by the German Federal Government in 2011 [12]. In the international environment, the terms IoT [13], Industrial Internet of Things (IIoT) [14], and Cyber Physical System (CPS) [15] are associated with each other or used as synonyms [16–18]. Regardless of this, all of these terms are collective terms with a strong marketing character [10,19,20].

There is agreement on the term Industry 4.0, mainly in the distinction between the previous development stages: Industry 1.0, which is characterized by the use of complex mechanics and the introduction of steam engines in production processes; Industry 2.0, which is characterized by the use of assembly lines, the use of electrical systems, and mass production in general; Industry 3.0, where computers and a highly automated system were introduced into production; and Industry 4.0, which is characterized by the networking of previously automated processes and the utilization and processing of large amounts of data using new concepts and technologies [21,22]; see Figure 2.

It is important to note that both terms, digitalization and Industry 4.0, are intertwined and difficult to differentiate from one another [10,23,24]; see Figure 3.

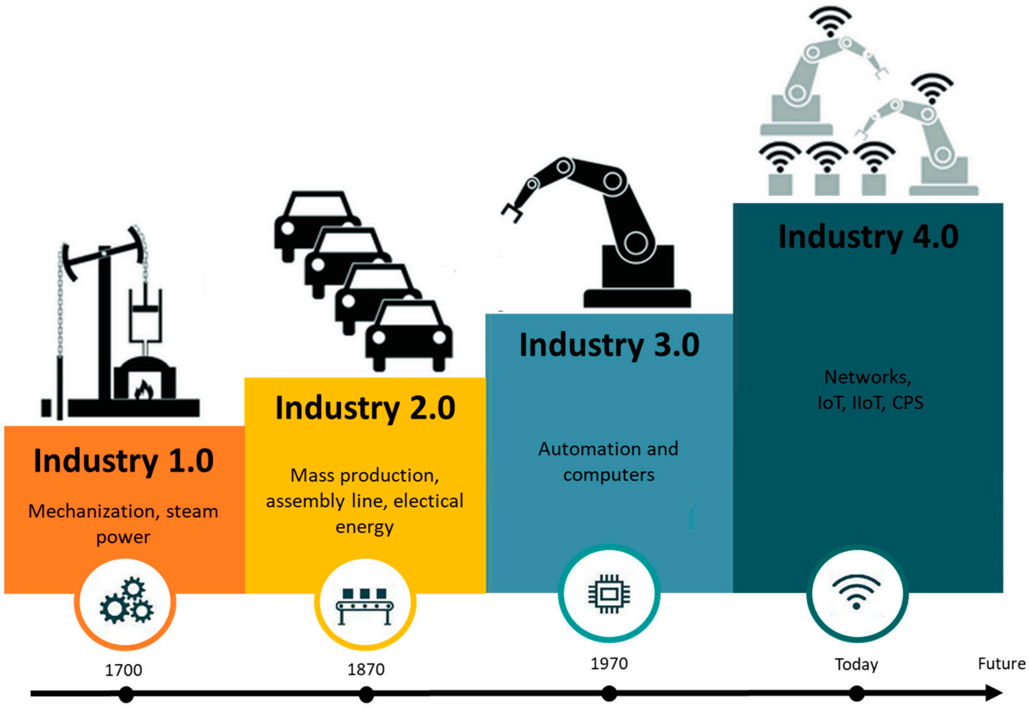

Figure 2. Industry 1.0 to 4.0 [21,22].

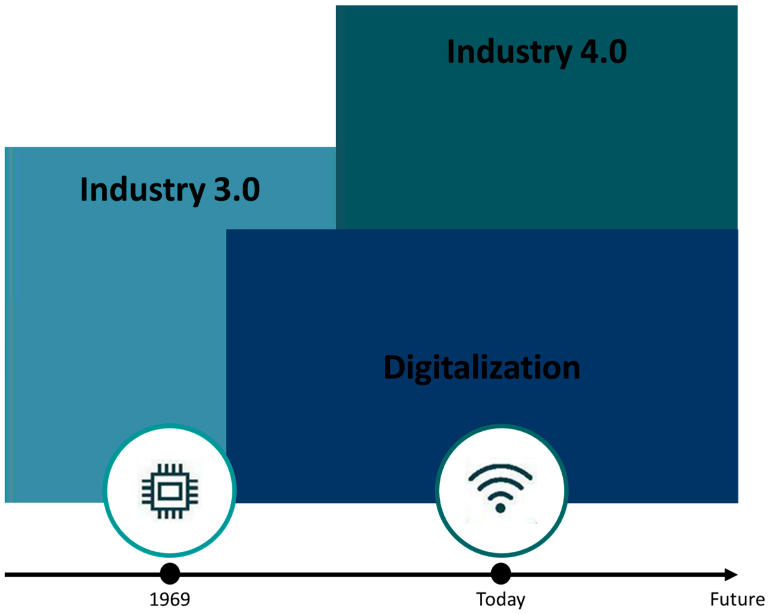

Figure 3. Overlap of the topics Industry 3.0, Industry 4.0, and digitalization [10,23,24].

3. Paper Scope

The focus of this work is on the identification of technologies and functionalities of digitalization with reference to Industry 4.0, which are directly connected to machines and their implementation in an industrial environment.

The distinction between technology and functionality with regard to digitalization and Industry 4.0 is based on the following question: how is it possible? This corresponds to the question of the necessary technology and the following question: what should be achieved? This further corresponds to the consideration of functionality [25].

Technologies and functionality are only related to digitalization and Industry 4.0 if they can be maintained through communication or networking with other systems [26,27].

Information Technology (IT) solutions that are designed as standalone solutions are not included [28].

For the machine, the core competence lies in receiving data from other physical or virtual sources, in processing and generating new or additional information, and in passing this information on to physical or virtual recipients; see Figure 4 [29]. However, the interpretation of the data and the measures derived from them lie outside the core competence of the machine. This lies in network-based services [30,31], which are either provided by third parties or made available directly by the machine manufacturer in the form of digital tools (apps) as a separate product [32,33].

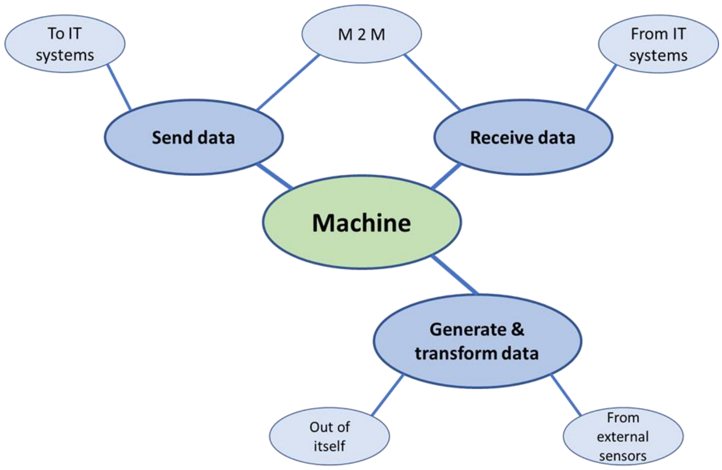

Figure 4. Core competence machine in digitalization and Industry 4.0 [29].

In terms of the literature, this paper will focus on the literature in English and German because mechanical engineering and the manufacturing/processing industry are highly relevant to the United States of America (rank 2) and German (rank 3); the Chinese literature (rank 1) [34], if not available in English, could not be integrated because of language barriers. In the sections in which statistical methods were applied to the published literature, a holistic approach was chosen due to the manageable number of relevant publications in German, while publications in English were analysed on a random basis.

4. Development of Technologies from Industry 3.0 to Industry 4.0

How communication between machine and software can be established corresponds to the question of technology. A distinction can be made between the hardware aspect and the type of communication [35].

Depending on the machine age, the requirements for the quality of the data, and the financial scope of the user, there are different options for data acquisition in the machine [36]. As a result, the options used by the physical components of machines to communicate with other systems vary greatly, from connecting the machine and sensors using input/output (I/O) modules, the simplest solution for converting analogue data from the machine into digital information, to the direct integration of programming logic controllers (PLCs) into data acquisition [37].

Regardless of the physical component through which communication is implemented, the way in which the recorded information can be made available to the outside world differs greatly depending on the age of the solution used [38]. "The limiting factor for application in manufacturing today, however, lies in the interfaces between production facilities and cloud infrastructures" [39].

4.1. Hardware

At the beginning of the development of data transmission in the 1980s, information was transmitted between machines and software systems via separate hardware interfaces [40]. Individual market participants tried to establish standards based on their own components. Common formats were, for example, teletype (TTY) or Multi Point Interface (MPI)/DisplayPort (DP) [41].

With the rise of the Personal Computer and the spread of the Internet in the mid-1980s, Ethernet, and thus the category cable system (CAT), became the norm, and the standard RJ-45 connector also became established in industrial applications [42]. Colloquially, the combination is referred to as a Local Area Network (LAN).

With the introduction of driverless transport systems and the use of tablets and mobile phones in the industrial environment, Wireless Local Area Network (WLAN) technology is also gaining importance. However, it is rarely used in the area of data transmission from machines, as the requirements for availability, latency, and connection security are high, which can usually only be ensured by expensive industrial WLAN networks [43]. In addition to these technical thresholds, the standard installation of WLAN modules directly in/on machines is not yet very widespread, which means that LAN connections are used, which are now available in all modern machines. The use of 5G technology is generally in its infancy, and so far, there are neither use cases nor reliable data on the benefits and costs of this technology in the field of machine communication [44–46].

With regard to the question of how data are collected, two phases must be considered. At the beginning of digitalization, there was a strong focus on fast and simple machine linkages [47]. I/O modules or I/O links were used for this purpose. This involves the installation of separate, machine-independent hardware for recording and converting electrical and physical signals into digital information. This is a fieldbus-neutral standardized point-to-point connection. This separate hardware has a network connection via which the information is provided [48].

Machines produced after the year 2000 usually have an integrated LAN network connection [49]. This is contained in the PLC and is used to transfer information. Alternatively, there are also solutions in which the physical server systems are linked to the controllers. In these cases, the machine already provides services in addition to the pure data [50].

4.2. Communication Standards

When it comes to communication, the question of how data are interpreted in a standardized way between sender and receiver must be resolved. At the beginning of digitalization, data were sent through fieldbus-neutral, standardized point-to-point connections using telegrams [48].

As development progressed, further options for machine communication with IT systems were developed. Some of these were further developments of existing technologies and protocols from the previous automation phase, as well as new developments [38]. The types of communication that became established in the field of machine communication were the possibility of communication via Transmission Control Protocol (TCP)/Internet Protocol (IP) and User Datagram Protocol (UDP). Machine communication via TCP/IP involves several protocols for data transmission from machine to IT system [38]. The modelling is based on the International Standards Organization (ISO)/Open Systems Interconnection (OSI) reference model, whereby the TCP/IP model represents a condensation; see Figure 5 [51].

This connection of protocols is very important because, among other things, it forms the basis of Internet communication. It includes Ethernet, which describes both the hardware configuration itself and the protocol used to ensure network access; the IP protocol, which forms the basis of the other protocols and takes on the task of switching from sender to receiver; and the TCP protocol, which splits up the individual data blocks and reassembles them correctly on the receiver side. In addition, the TCP protocol has the ability to request lost data packets again [38].

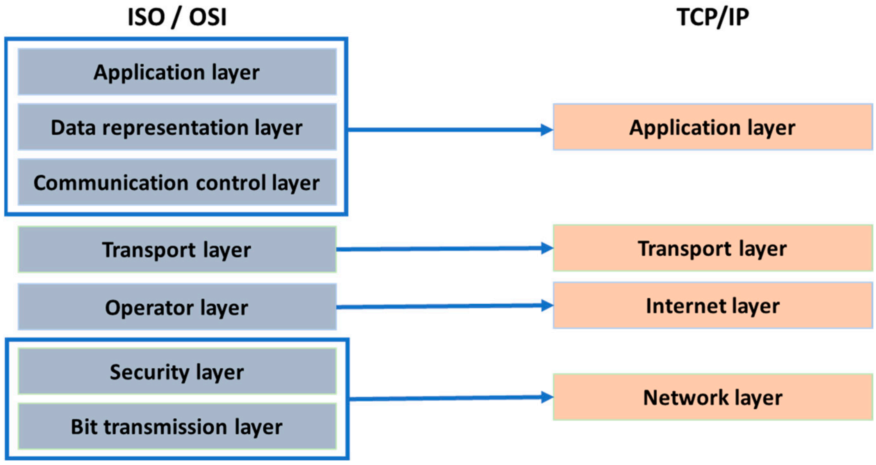

Figure 5. Comparison between the layers of the TCP/IP and ISO/OSI reference models [51].

Machine communication via UDP is a method that is similar to the TCP/IP protocol. The major difference from the point of view of machine communication to the TCP/IP protocol is that, with UDP, there is no bidirectional communication with the receiver, but the data are provided once by the sender and a new request for a data packet, e.g., in the event of loss or inconsistency on the part of the receiver, is not possible. The advantage of this method is that larger quantities can be provided more quickly with less bandwidth [52].

4.3. Machine Communication

In the following section, the procedure for data exchange from machine to higher level software system in the transition period from Industry 3.0 to Industry 4.0 will be explained using the examples of EUROMAP 63 [53] and the Hypertext Transfer Protocol (HTTP) [54].

An example of machine communication that was developed directly by machine builders in the 1990s is EUROMAP 63 for the plastics industry. This uses the CCP Protocol, in which, among other things, network communication is described using TCP/IP and data exchange [55,56]. In practical application, this means that a data package or program file is created by the machine, e.g., ".csv", and stored in a folder within the machine or on a server or, in the case of bidirectional communication, retrieved from the folder by the machine [57]. The type of file, as well as the data content, including syntax, is created directly in the machine controller by the protocol implemented on it. With this type of communication, the result is defined via the standardized protocol, and the implementation is left solely to the machine manufacturer [56].

Another example of communication in the transition period between Industry 3.0 and Industry 4.0 regarding data exchange from machine to higher-level software system is communication via HTTP. Although its development predates the World Wide Web, it became relevant only with its breakthrough in the 1980s. Existing World Wide Web structures and protocols, including TCP/IP, for example, are used for machine communication without there being a standard for the data content. With this approach, the type of communication is specified, but the content must be agreed between the customer or the software manufacturer and the machine manufacturer [58,59]. In addition to the specification of the data content, it should be noted that data exchange via HTTP is unencrypted; this was solved by the successor protocol Hypertext Transfer Protocol Secure (HTTPS) from 1994, which is still common today [60].

4.4. Industry 4.0 Communication Standard: OPC UA

Since the mid-2010s, machine communication via Open Platform Communications Unified Architecture (OPC UA) has established itself as the standard for new machines [61,62] regardless of whether they communicate with IT systems or with other machines, known as machine-to-machine (M2M) communication. OPC UA is subject to continuous further development [63] based on the TCP/IP protocol and following the OSI model [64]. The aim of OPC UA is to create a way to transfer data in a manufacturer-independent, standardized way. Care was taken to avoid the weaknesses of older protocols, including platform dependency and security vulnerabilities [65,66]. The framework conditions for this are defined by the OPC Foundation, an association of various stakeholders in industry and research. The standardization carried out by the OPC Foundation is limited to the definition of basic structures, which still leave machine manufacturers the option of individual design. In addition, standardization offers the possibility of developing the so-called companion specifications. These are information models with which machine signals and other information modules can be defined, depending on the type of industry in which the machine is to be used [67]. Examples of such specifications are the "OPC for Machinery" [68], which applies to mechanical engineering in general; the "EUROMAP 77" [69] or "OPC-40083" [70] for the plastics processing industry; and the "OPC-40600 Weihenstephan Standards" [71] in the food and packaging industry.

The ability to flexibly adapt OPC UA to future requirements is ensured by the manufacturer's independence of both the hardware and the machine software, as well as the expandability to include new communication protocols and programming languages for implementation.

This flexibility and independence, which characterizes OPC UA, allows the systems of all controller manufacturers to be used. All leading control system manufacturers have developed and offer applications for OPC UA communication. However, it is also possible to use third-party systems as long as they are able to access the controller itself [72]. The decisive factor in this decision is the desired degree of harmonization of the IT infrastructure.

4.4.1. OPC UA Machine Communication

When communicating data from machines to IT systems, OPC UA uses either a client-server architecture [64] or the so-called publish–subscribe method [73]. In the much more widespread client-server architecture, the machine is usually the server, while the IT system is the client [74]. The server in the machine allows queries and conditions to be generated directly from the raw data of the machine and thus forms an initial filter. The client's implementation in the area of IT systems has the advantage that different software agents can access the server's data independently. However, it is also possible that both server and client are implemented in IT systems, whereby in this case, the central (aggregation) server serves as a middleware for forwarding data; see Figure 6 [75].

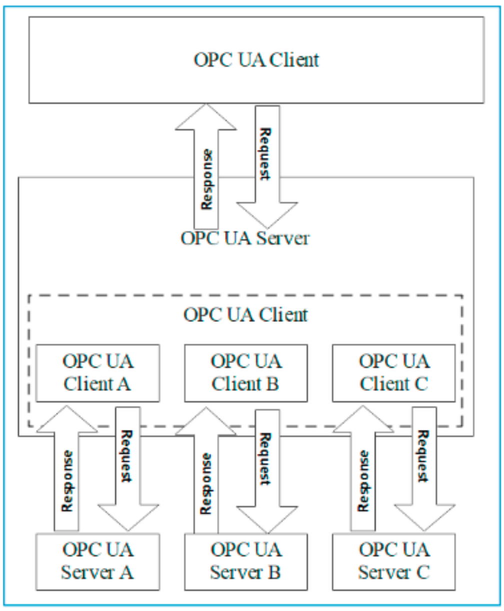

Figure 6. Example of client server structure with middleware [75].

In M2M communication, both machines can act as both server and client; see Figure 7 [76].

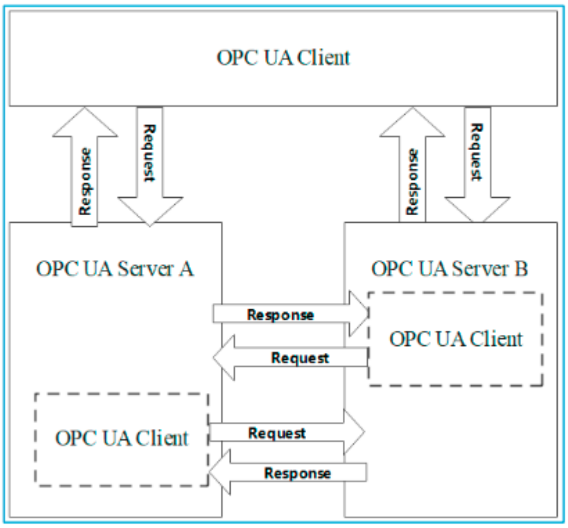

Figure 7. Example structure for M2M communication [76].

With the PubSub method, data can be provided by different machines or senders (publishers) and retrieved by one or more data processors (subscribers) via a message broker, depending on the network architecture, in contrast to the client–server system [73,77,78]. See Figure 8.

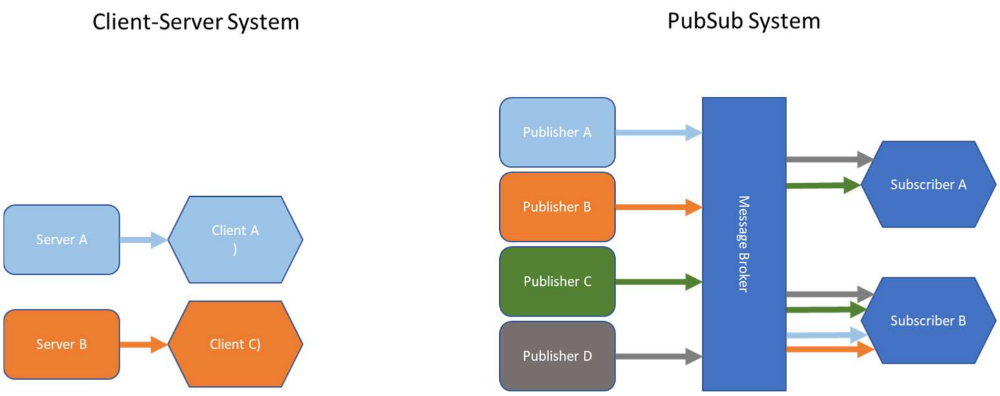

Figure 8. Comparison of client-server to PubSub communication [78].

4.4.2. Advantages and Added Value of OPC UA for Mechanical Engineering

The benefits of using OPC UA for machine builders can be summarized as follows [79–81]:

- Spreads an increasing acceptance of OPC UA as a communication standard between machines and higher-level software systems;
- Generally defined structures for creating models for processing and transferring data from machines to higher-level systems;
- The expandability of the structure due to modularity and object orientation;
- Industry-specific company specifications are provided for special cases in the respective industry sector;
- Independence of the general OPC UA concept from hardware and software;
- Integrated security architecture for data exchange.

4.4.3. Limitations of OPC UA

Like all technical systems, OPC UA has defined use cases which are achieved, among other things, when data need to be exchanged at high speed. This involves data that need to be captured and processed at intervals of a few milliseconds. Deterministic communication using server–client systems takes around 200 milliseconds, depending on the hardware and software. Intervals shorter than 200 milliseconds carry the risk of data loss or inconsistency in data processing, as shown in the studies by Pott and Dietz [82] and Nakutis et al. [83]. The reason for this limit is the latency between the individual systems that are linked using OPC UA. This means that OPC UA is not capable in real time with the current standard server–client configuration and is therefore not suitable for monitoring and controlling robots, for example, with control intervals in the range of 10–15 milliseconds [49]. This disadvantage can be eliminated in the future with the use of PubSub and/or Time-Sensitive Networking (TSN) [49,84].

5. IT Functionalities in the Field of Mechanical Engineering

Functionality refers to "the property of a thing of being very well suited to the purpose for which it was designed" [85]. In this section, the IT functionalities that are directly related to machines and are therefore relevant for mechanical engineers who want to become active in the field of digitalization and Industry 4.0 will be determined and described on the basis of scientific publications.

5.1. Determination of Relevant IT Functionalities

To determine the relevant topics, discussions were held with people from the fields of mechanical engineering, production management, and production software in order to gain an impression of the range of functions and functional requirements. The identified functionalities were then compared with and evaluated in anthologies on the topic of Industry 4.0 with different focal points.

The evaluation was carried out using a three-level categorization from zero to two, whereby the categorization was carried out as follows:

2 = Is explicitly dealt with in connection with machines

1 = Mentioned in connection with I 4.0 or digitalization

0 = No mention

(Appendix A, Table A1)

The summed values then allow for an assessment of the relevance of the functionality as well as the relevance of the collective work to the overarching topic overview of technology and functionality standards of digitalization in mechanical engineering.

In addition, a keyword search was carried out via "Google Scholar" for the number of publications on the relevant functionalities in both German and English. Depending on the result, a specific term was searched for, and if the number of hits was low, the procedure was repeated with a simplification (secondary term). With this procedure, it occurred that publications that come from a subject area other than the one referred to were also counted, especially when searching with secondary terms in the English language. Therefore, a search was carried out using the IEEE Xplore system in the digital library, an English-language library for the subject areas of computer science, electrical engineering, and electronics and related areas (Appendix B, Table A2).

5.2. Functional Description

The following section describes the functionalities identified and explains their relevance and categorization in relation to mechanical engineering. The order is roughly based on the chronological order in which the functionalities appear.

5.2.1. Remote Management/Remote Access/Teleservice

Remote management, or its synonyms remote access and teleservice, refers to the possibility of remotely accessing the control of a machine, reading and/or exchanging information, or taking over the control of the machine [86].

The importance of this topic for the mechanical engineering industry becomes clear when you consider that teleservice has to be taken into account right from the design phase. "In order to be able to offer customers faster fault diagnosis, a more efficient repair service and better advice, it is necessary to be able to monitor the operating status of your own products while they are in use at the customer's premises. For such efficient teleservice solutions, the machines for which teleservice is offered as a product-accompanying service should be designed from the outset" [87]. The topic itself has been known for some time [88,89]. However, in the years of the coronavirus pandemic and due to the progressive shortage of skilled laborers, new impulses have been set, which have led to both the future development of existing concepts and new collaborations between classic machine components and new market participants for mechanical engineering [90,91]. This development has led to the availability of well-functioning plug-and-play systems that can be used by machine builders to establish a remote connection to machines [92]. The current challenge in this area of mechanical engineering arises from the fact that people outside the company are granted access to machines and, possibly, the company network [93,94]. The associated risks for machine manufacturers and their customers, in an age in which not only criminals but also states attack IoT networks, cannot be neglected [95,96].

As the use of such systems is established in the field of mechanical engineering and saves costs for both customers and machine manufacturers [97], such systems are the standard for mechanical engineering companies involved in digitalization [98].

5.2.2. Machine Data Collection (MDC)

Machine data collection, or machine data acquisition, contains, in contrast to process data and condition monitoring data, rudimentary signals from the machine that provide information about the operational status and production performance of a machine [99].

MDC data are the basic elements of the digitalization of production, as they are sent automatically to higher-level systems, and the information, supplemented with other data, forms the basis for all further evaluations of the machine [100]. It is generally a prerequisite for all further Industry 4.0 technologies [101–103]. "The MDC module provides real-time data from production. Monitoring and alarming in particular, but also maintenance, traceability, or detailed planning, use the data provided by the MDC" [104,105]. The minimum requirements for MDC are the collection of data to determine availability and performance, which means data on production time, good part quantities, and scrap quantities, as they are also used, for example, to determine acceptance-relevant key figures [106]. These data can be collected through I/O modules. For machines with directly integrated MDC, additional information on the status of the machine can be recorded here, e.g., production interruption, malfunction, and cause of malfunction. This allows the Overall Equipment Effectiveness (OEE) and its individual elements to be determined in higher-level systems without further human intervention [107].

For the machine manufacturer dealing with the topic of digitalization and Industry 4.0, this means that a machine must provide these data in a common data format, since, as already mentioned, MDC forms the basis of digitalization.

5.2.3. Energy and Consumption Data Acquisition

Energy and consumption data acquisition, with regard to the use of machines, involves data that are collected on consumables that are used and measured directly on the machine [108].

Examples of direct variables are power consumption, water consumption, gas consumption, etc., which are recorded both during production and downtime [109], while indirect variables such as the "carbon footprint" are determined outside the machine [110,111].

Depending on the industrial sector, there are legal requirements that define which data have to be collected, such as the "Energy Efficiency Directive 2012/27/EU" [112] or the "Industrial Emissions Directive 2010/75/EU" [113]. Parallel to this, there are also industry standards that define what should or must be recorded [114]. In addition to the legal requirements, however, more and more companies are interested in recording the consumption data of their machines, either to reduce consumption or to fulfil their own ambition of operating more sustainably [115]. There are separate hardware components for recording these data, which can be installed independently of the machine manufacturer. For machines that already have the appropriate internal hardware, this information can also be provided through the control system [69].

As legal and social requirements in this area will continue to increase [116], it makes sense for mechanical engineering companies to expand their sensor technology in this respect and to provide data on energy and media consumption in an open and standardized form. Depending on the industry and the size of the machine buyers, it may also make sense to provide software modules that interpret these data.

5.2.4. Process Data Acquisition

"With process data acquisition, the production process itself is monitored and the respective states are recorded. Process data can be used for evaluation or for further processing in a control loop" [99]. For new machines and systems, environmental and production parameters are recorded directly for the product to be manufactured [117].

This usually serves the purpose of quality assurance or continuous process optimization. This can involve data that are generated and influenced directly at the machine, such as speeds, injection pressure, and feed rate, as well as data that are recorded purely for documentation purposes, such as material temperature, material flow, and viscosity, from the product being processed. These are recorded by the machine's sensors and passed on to higher-level systems via its control system [118,119]. In addition to these variables that can be assigned directly to the product, environmental parameters are also recorded, including, for example, humidity and room temperature, which are transmitted to the machine via separate sensors [120,121].

For mechanical engineering, process data can be a unique selling point compared to software providers, as the processes cannot be generalized on the same scale as the previous topics. Machine builders, especially manufacturers of individual machines and small series, usually know the specific processes of their systems and the corresponding requirements of their customers very well, which allows them to provide a generalized data offering that is individualized for the customer [122,123].

5.2.5. Condition Monitoring

With condition monitoring, the focus is on the machine itself, in contrast to process data acquisition, which are why data are collected over the entire service life of a machine [124].

Information such as force, power, and pressure curves or the vibration behavior of individual machine components is recorded via sensors and forwarded to higher-level systems, where the analysis takes place [125,126]. Machine builders can determine which individual elements should be monitored using classic Failure Mode and Effects Analysis (FMEA) [127] based on empirical values or, if available, failure statistics. The correct choice of data filter must be considered, which must already be applied in the signal generation in the machine. The signals can be subdivided into data to be recorded permanently, snapshots, or the observation of maxima [128,129]. In all of these cases, the machine has the role of data generation and forwarding [130].

As there are no legal requirements for condition monitoring, it is difficult to realize and amortize as a functionality for machine manufacturers, apart from specific customer requirements [131]. In addition, there are competitors in the software sector who sell corresponding sensor modules in a package with software applications. However, condition monitoring forms the basis for the "preventive maintenance" described in the following section, which can become an exclusive business area of machine construction [132].

5.2.6. Predictive Maintenance

The topic of predictive maintenance in the context of digitalization or Industry 4.0 is made possible by functioning condition monitoring. The aim is to predict when individual components will fail based on the data collected by the machine itself or with sensors connected to the machine [124].

Determining failure scenarios requires a large amount of data on failure scenarios that must already be available [48]. For ongoing operation, it is also necessary to collect and store the data required to determine the probability of failure of a machine over very long periods of time; time intervals of several months, but also over several years, are not uncommon [133,134].

The advantage of this Industry 4.0 functionality for the machine manufacturer compared to the other Industry 4.0 functionalities presented is that it is a software application based on machine information. It can be used to directly realize new business models in mechanical engineering that can be integrated into the existing value chain of machine manufacturers, for example, maintenance and spare-part supply contracts based on failure forecasts. This offers the customer the benefit of increasing the availability of their machine and reducing the need to maintain their own resources, as well as reducing costs for machine builders who can optimize the use of their own capacities through better use and additional income through support activities [93,134,135]. The necessary IT infrastructure and database expertise can be provided by the machine manufacturer themselves, by third parties, or, in the case of larger company units, directly by the customer themselves [136].

5.2.7. Order Management

As a cumulative data point in information processing in production, the order is of particular importance as a link between the producing element, the machine, and the recording systems [137,138].

Therefore, a machine operating in such a network must also be able to receive, process, and forward order information to other network participants. The way in which the order and the associated information is handled is highly dependent on the requirements of the respective authorization concept of the manufacturing company and the production IT infrastructure that is used there [139]. This makes the implementation of order management in a machine more difficult, and two aspects must therefore be taken into account for the machine manufacturer [140].

Firstly, the degree of automation in the decision-making process for an order, on the part of the machine manufacturer's customers [141]. Most companies are in the range between Level 2—"The technology offers a complete list of possible alternatives"—and Level 5: "The preferred alternative is executed if confirmed by a human". Higher levels can only be achieved by companies that also use other automated systems that do not require any further human interaction, such as artificial intelligence (AI)-supported detailed planning or autonomously operating production networks [142]. This aspect defines the physical elements for data selection and provision, as well as the type of data processing in a machine.

Secondly, the data structure, which, in most cases, is specified by higher-level systems, is mainly derived from the master data of the Enterprise Resource Planning (ERP) system [143] but can differ due to different production concepts such as series production, batch production, single-part production, etc. [144]. Current interfaces for individual industries have already taken this into account and developed structures [70]. Several cross-industry specifications are currently being developed with the aim of providing a homogeneous definition for order data structures for machine manufacturers [68,145].

5.2.8. Distributed Numerical Control (DNC)

Distributed Numerical Control, or program management, refers to the assignment of a machine program to the machine, depending on the product to be manufactured and other parameters such as the machine itself, tools, raw materials, etc. [146].

In machines with program management, as soon as the frame parameters are known, the corresponding program is loaded from a storage location onto the machine and released for production [107]. The advantage of this type of program management is that it is based on rules, and therefore, it is also possible to ensure that only approved programs are used. Furthermore, it reduces the effort and complexity in production itself, as the organization, allocation, and transport of physical storage media, such as memory cards, are no longer necessary [147].

For the machine manufacturer, it should be noted that it is not absolutely necessary that the machine programs themselves are readable for the functionality that controls the exchange, but only that the machine program is clearly identifiable and there is a possibility of exchange [148].

5.2.9. Product Tracking and Batch Recording

Batch recording and product tracking are processes that are strongly characterized by legal aspects and serve to reduce recalls and recourse costs [149].

For implementation, the data on production, preliminary products, raw materials, and, if applicable, customer allocation must be available and be able to be allocated to the individual product or batch [150]. Normally, the primary information 'batch' is not produced by the machine but is taken from other systems and expanded into a new data set [151]. However, the machine must be able to record, process, and supplement data. To do this, the data are either collected manually via a Human–Machine Interface (HMI), external sensors such as Radio-Frequency Identification (RFID) readers, barcode scanners, or camera systems, or provided by another system [152]. Batch data can then be forwarded to the higher-level IT system to provide an overview of the product [153].

The machine usually serves as an intermediary for the data between the element to be recorded and the higher-level systems. The reason why data are recorded in the machine is that batch data can no longer be resolved after processing in the case of incoming batches [154], while the generation of outgoing batches directly after the production process ensures that all production process data are recorded with batches [155].

5.2.10. Tool Data Acquisition

Like batch recording, tool data recording in a machine is a function in which data recorded as part of other functionalities are added to a new set.

While, in batch recording, the place where the product is created or the components are converted is decisive for data recording, in tool management, it is the use or place of use of the tool, usually the machine. Added to this is the fact that tools are currently only able to capture and forward data in a few cases [156,157], combined with the fact that a large part of the data required to manage the tools is generated redundantly during processing on the machine [158,159]. However, tools have a major influence on production and quality, so monitoring and documentation are important for machine manufacturers' customers.

From the machine manufacturer's point of view, it is sufficient if the machine additionally records the tool currently in use via the machine and communicates with the data, e.g., from the MDC. Further processing and storage can then take place in separate systems [158–160].

5.2.11. Recording of Personnel Data

Personnel data acquisition within a machine is relevant when data requiring documentation can be added to or manipulated directly by the machine and forwarded from there to other systems. This includes the machine program, specification of statuses, maintenance data, and order information [161].

It must be ensured that it is possible to attribute the manipulation of the data to an employee. The recording of personnel data in machines is subject to the documentation obligation with regard to traceability on the part of the legislator and the end customer [162], and not personnel data recording in the sense of personnel management and personnel control, which are subject to laborer law or business management aspects compared to Schimmelpfeng [162], Wienkamp [163], and Wojak [164]. The employee can be recorded by a machine, either by directly entering the identification element, e.g., clear name, ID number, personnel number, etc., in a machine HMI or via separate hardware elements such as RFID token readers [165,166], or the information is forwarded directly to the machine from a third-party system, e.g., Manufacturing Execution System (MES), time recording, etc. [167].

The integration of appropriate hardware and software interfaces by recording personnel data is the primary requirement for the machine manufacturer.

In addition to the software applications listed in the previous paragraphs, there are other applications from the field of mechanical engineering that will not be discussed further. These are applications that are relevant for specific machine types, such as integrated quality assurance and visualization solutions, that cannot be generalized. Also of note are machine-related software applications that exceed the development capacities of traditional mechanical engineering companies or whose development stage and market penetration are still in their infancy, such as the topic of digital twins or AI-based applications.

6. Research for Industry Transfer

In the following section, the state of research on the implementation of the functionalities described in the previous section in practice will be determined. The focus here is on empirical data on the implementation and application of the functionalities mentioned.

6.1. Procedure

A multistage literature search was used to determine the current state of knowledge for implementing the functionalities described.

In the first step, Google Scholar was used to query publications with the search terms survey, Industry 4.0, and mechanical engineering (in German) for a period of 3 years, and the texts were analyzed, evaluated, and classified for data with corresponding content. The evaluation was based on a four-level categorization, which was carried out as follows:

- Category 1: Publications on the topic of Industry 4.0 in which the areas of mechanical engineering and production are explicitly considered;
- Category 2: Publications in which the results deal with tactical topics and individual overarching functional aspects of the field of mechanical engineering. Examples of this are [168,169];
- Category 3: Publications in which survey results deal with strategic or tactical topics in the field of mechanical engineering; functionality aspects are not considered. Examples of this are [170,171];
- Category 4: Publications that focus on topics outside of mechanical engineering or where statistically usable data are not available [172].

The query was then conducted in English, and, due to the higher number of publications, was randomly analyzed for convergence with the first query.

In order to take the individual functionality aspects into account, the query was repeated with the search terms survey, mechanical engineering, and the corresponding functionality term and divided into three categories:

- Category 1: Publications in which the survey explicitly considers the functionality aspects of the field in relation to mechanical engineering or production;
- Category 2: Publications in which the survey considers functionality aspects;
- Category 3: Publications that focus on topics outside of mechanical engineering or where statistically usable data are not available.

At the same time, a search was carried out in Statista, a German-language library of statistical publications, for any publications with the terms Industry 4.0 and mechanical engineering and the tags machinery, plant engineering, and Industry 4.0.

6.2. Result

The following section summarizes the results of the research from Section 6.1 and is summarized below.

For publications in Google Scholar with the search terms "survey", "Industrie 4.0", and "mechanical engineering" in German for a period of 3 years up to 31 October 2023 (n = 435), see Figure 9.

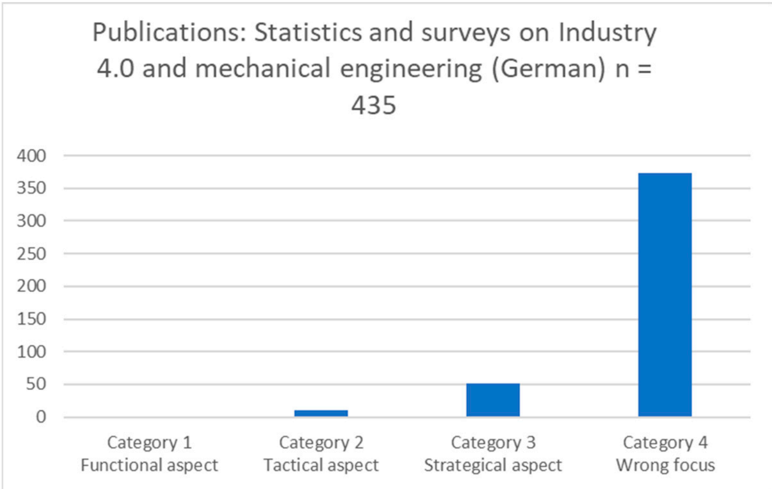

Figure 9. Publications on statistics and surveys on the topic of Industry 4.0 and mechanical engineering.

For publications in "Google Scholar" with the search terms "Survey", "Industry 4.0", and "Mechanical engineering" in English for a period of 3 years up to 31 October 2023 (sample n = 30), see Figure 10.

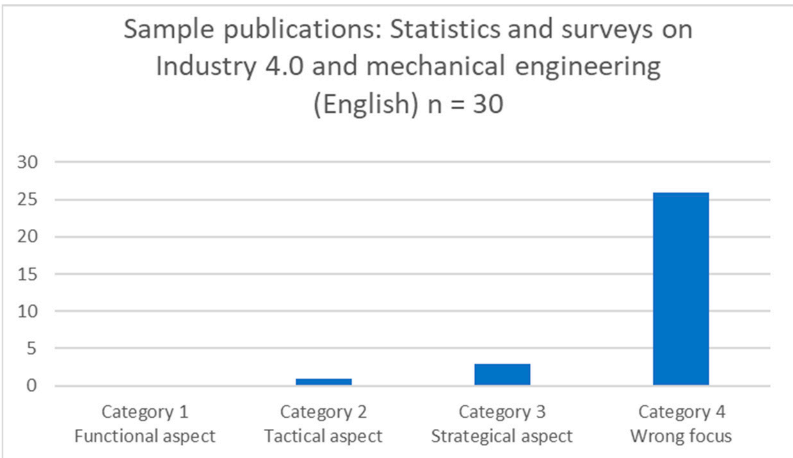

Figure 10. Sample of publications on statistics and surveys on the topic of Industry 4.0 and mechanical engineering.

For publications in "Google Scholar" regarding the terms "Survey", "Mechanical engineering", and the corresponding functionality term in German for a period of 3 years up to 31 October 2023, see Figure 11.

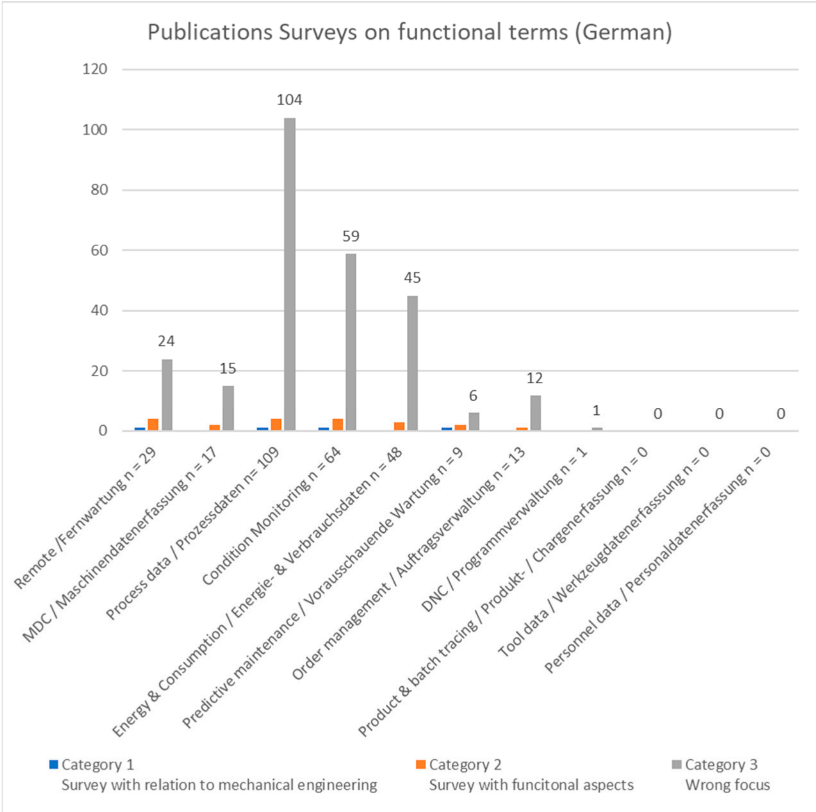

Figure 11. Publications: surveys on functionality terms (German).

The search carried out in Statista for the period of 2016 to 2023 with the terms "Industry 4.0 and mechanical engineering" and the tags "machinery and plant engineering" and "Industry 4.0" resulted in 50 hits, which can be classified into two categories: statistics that deal with the topic strategically/generally (n = 29) and statistics unrelated to the topic (n = 21). However, the 29 strategic/generalist statistics can be traced back to seven publishers: Statista, Bitkom, EY, Commerzbank, Fraunhofer, Horvath & Partner, and McKinsey. Statistics that explicitly deal with the functions of machines with regard to Industry 4.0 could not be found in Statista.

In general, very little statistical material on the use of software in the manufacturing industry was found in all searches for scientific publications. The few sources that were available mostly had a commercial rather than a technical background.

7. Discussion and Conclusions

As this paper on the terms Industry 4.0 and digitalization shows, the revolution in the field of mechanical engineering, or Industry 4.0, is more of an evolution than a revolution. A large part of the technology and functions existed before the term was defined and has been adapted to the further development of the technology.

As can be seen from the technological development in the section entitled Development of Technologies from Industry 3.0 to Industry 4.0, a technological standard has been established in mechanical engineering, both on the hardware side with LAN/Ethernet and in the area of data communication with OPC UA. On the hardware side, LAN/Ethernet will remain the dominant technology in machine communication, as there is currently no technical need to replace or dismantle existing network structures, the alternatives are not sufficiently adapted to the needs of modern production, and the payback period in mechanical engineering is generally long, making it difficult to change hardware. The situation is different when it comes to the aspect of the open communication protocol, OPC UA. This will also gain market strength, but for different reasons. The continuous development and integration of new digital methods and technologies that build on or complement each other adds to the continuity that machine builders need. The result will be that once an investment has been made, it will still be of value in later phases.

The 11 functionalities that have been identified and presented here currently form a basis that a machine manufacturer in the current market environment must be able to master or at least work on implementing in order to avoid being replaced by software or third parties and losing control of their product. From a scientific point of view, the relevance of these technologies is undisputed. This is demonstrated by the fact that they have found their way into the relevant textbooks.

Regulatory requirements and customer demands are the main drivers of the implementation of these functions. From the machine manufacturer's point of view, the IT functionalities in demand by legislators and customers are mostly requirements for pure data provision. However, machine builders should also have an interest in the further development of their own products and services and in being in a position to amortize this development themselves. This is especially true for functionalities where data become relevant for their own new services, which can be unique selling points against third parties.

Mechanical engineering companies, which also deal more intensively with the topics of Industry 4.0, digitalization, and related concepts, ensure that their IT products are not replaced by third parties or that their previous developments become obsolete. Since IT solutions in the mechanical engineering sector in particular are expected to function faultlessly and in the long term, the decision on the extent to which capacities are created or tied up must be weighed up carefully, because once the provision of additional software has begun, it will be expected by customers in the future. This is especially true for SMEs, which need to consider whether they have the capacity to do more than provide data.

This study also showed that theoretical knowledge is available and that there are lighthouse projects that have been developed in cooperation between research and practice.

As far as the data situation on Industry 4.0 in practice is concerned, the majority of the publications found do not deal specifically with the aspect of mechanical engineering or only provide an assessment of the general future prospects of Industry 4.0 in the field of mechanical engineering. However, there is little statistical data on the implementation of technologies and functions in mechanical engineering or in the user industries. This information would be particularly important as a decision-making aid for mechanical engineering companies in order to be able to assess the above-mentioned decisions with regard to the corresponding capacities to be created.

From a scientific point of view, the collection of statistical data on the implementation and validation of Industry 4.0 functionalities in mechanical engineering is the next necessary step to examine the extent to which Industry 4.0 is a revolution that will actually change the current industry worldwide. If this point is neglected, there is a risk that research based on the theoretical state of the art and "early bird" companies will build up too-high expectations that do not match real needs and opportunities. It is also important to identify potential barriers and challenges that hinder both the diffusion of skills among machine builders and their use by their customers.

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Appendix A

Table A1. Overview of the relevance of functionalities identified in anthologies on the topic of Industry 4.0, production, and machines [26,27,33,172–178].

Title	**Industrie 4.0 in Produktion, Automatisierung und Logistik**	**Einführung und Umsetzung von Industrie 4.0—Grundlagen, Vorgehensmodell und Use Cases aus der Praxis**	**Handbuch Industrie 4.0 Bd.4**	**Industrial Internet of Things**	**Betriebswirtschaftliche Aspekte von Industrie 4.0**	**Handbuch Industrie 4.0: Recht, Technik, Gesellschaft**	**Werkzeugmaschinen Fertigungssysteme 3**	**Digitalisierung Souverän Gestalten Innovative Impulse Im Maschinenbau**	**Digitalisierung und Künstliche Intelligenz in der Produktion**	**Innovations in Industrial Engineering**	**Evaluation of the Relevance of the Functionalities**
Year	**2014**	**2016**	**2016**	**2017**	**2017**	**2020**	**2021**	**2021**	**2021**	**2022**	
Functionalities											
Condition Monitoring	2	1	2	2	1	2	2	2	2	1	**17**
Process data acquisition	2	1	2	2	2	2	2	1	2	1	**17**
Energy & consumption data acquisition	2	2	2	2	2	1	2	1	1	1	**16**
Predictive maintenance	2	2	2	1	2	2	1	1	2	1	**16**
Remote management/Remote access/Teleservice	2	2	2	2	2	2	2	0	0	1	**15**
Machine data collection (MDC)	2	1	2	1	0	2	2	1	2	1	**14**
Tool data aquistion	2	0	2	2	2	1	2	1	1	1	**14**
Distributed Numerical Control (DNC)	1	2	2	2	1	1	2	1	0	1	**13**
Order management	1	2	1	2	1	1	2	0	1	1	**12**
Product tracking and batch recording	1	1	2	2	1	1	1	1	1	1	**12**
Recording of personnel data	2	1	1	2	1	2	1	0	0	0	**10**
Evaluation Relevance Source	**19**	**15**	**20**	**20**	**15**	**17**	**19**	**9**	**12**	**10**	

2 = is explicitly dealt with in connection with machines; 1 = is mentioned in connection with I 4.0 or digitisation; 0 = no mention.

Appendix B

Table A2. Publications.

			Remote Management/Remote Access/Teleservice	Machine Data Collection (MDC)	Energy & Consumption Data Acquisition
German		Search term	Fernzugriff Maschine	Maschinendatenerfassung	Energiedatenerfassung & Verbrauchsdatenerfassung
	Google Scholar	Number in total 06.2023	997	726	328
		Number in total 06.2023 Secondary term			
English		Search term	remote management	machine data collection	energy data acquisition & Consumption data acquisition
	Google Scholar	Number in total 06.2023	27,000	518	1969
		Number in total 06.2023 Secondary term			
	ieeexplore	Number in total 06.2023	393	11	104
		Number in total 06.2023 Secondary term			
German		Search term	Prozessdatenerfassung	Auftragsdatenerfassung (Auftragsmanagment)	Chargenerfassung & Produktdatenerfassung
	Google Scholar	Number in total 06.2023	567	65	37
		Number in total 06.2023 Secondary term		1640	
English		Search term	process data acquisition	Order data acquisition (Order management)	Batch tracing (Product tracing industry)
	Google Scholar	Number in total 06.2023	2420	112	196
		Number in total 06.2023 Secondary term		41,100	1,680,000
	ieeexplore	Number in total 06.2023	85	1	1
		Number in total 06.2023 Secondary term		142	369

Table A2. *Cont.*

			Remote Management/Remote Access/Teleservice	**Machine Data Collection (MDC)**	**Energy & Consumption Data Acquisition**
German		Search term	Werkzeugdatenerfassung (Werkzeugdaten)	Personaldatenerfassung	Programmverwaltung (DNC)
	Google Scholar	Number in total 06.2023	4	91	635
		Number in total 06.2023 Secondary term	692		3370
English		Search term	Tool data acquisition (Tool data)	personal data acquisition	Distributed Numerical Control (DNC)
	Google Scholar	Number in total 06.2023	180	317	865
		Number in total 06.2023 Secondary term	31,200		138,000
	ieeexplore	Number in total 06.2023	24	0	10
		Number in total 06.2023 Secondary term	646		177
German		Search term	Zustandsüberwachung	Vorbeugende Wartung Digitalisierung	
	Google Scholar	Number in total 06.2023	3050	1200	
		Number in total 06.2023 Secondary term			
English		Search term	Condition Monitoring	Predictive maintenance digitalisation	
	Google Scholar	Number in total 06.2023	402,000	15,000	
		Number in total 06.2023 Secondary term			
	ieeexplore	Number in total 06.2023	30,782	39	
		Number in total 06.2023 Secondary term			

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