A Literature Review of Digital Twins Based on Freely Accessible Scientific Papers

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A very positive fact is that there are a large number of journals that provide free access to science-based studies on the concept of digital twins. This easy and free access to relevant publications dealing with digital twins, and therefore offer a great opportunity to study the topic in more detail.

1 INTRODUCTION

A well-known search engine returns 2 730 000 hits for the term "Digital Twin". Apart from the marketing headlines, however, a large number of scientifically based publications are available. **Figure 1** shows an example of the result of the scientific online database ScienceDirect. It illustrates the development of the publications from 1995 to 2020 (please note the log scaling of the y-axis). The black squares show the results for all publications that refer to "digital twin" in any way within the text, while the blue circles show the results for "digital twin" with regard to title, abstract and key words (i.e. the more relevant publications). Regardless of the trends observed, it can be clearly seen that the number of publications increases from 2015 onwards, which is accordance with the representations of the development of simulation over time illustrated in **Figure 3**.

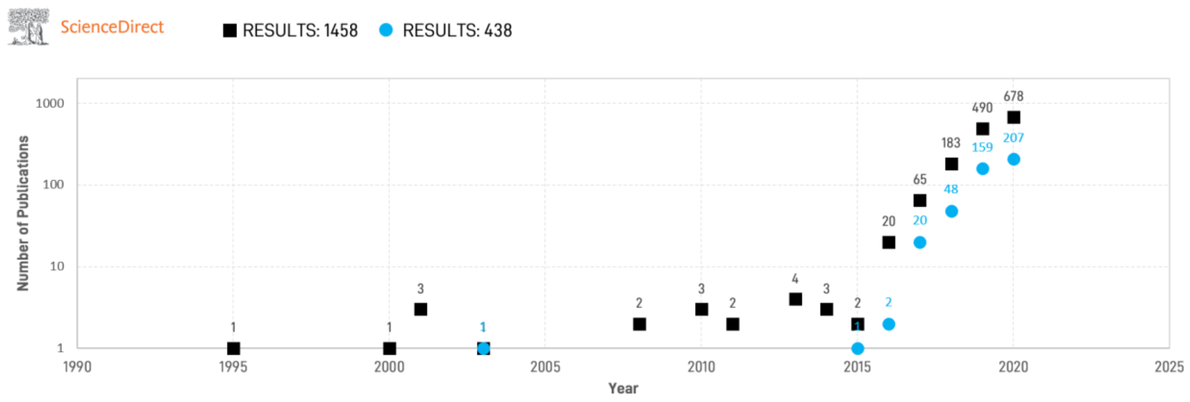

Figure 1: Number of papers dealing with digital twins according to scientific online database *ScienceDirect*

A very positive fact is that there are now a large number of journals that allow free access to publications. The following three journals are available as open access:

+ **Procedia CIRP (70)** is an open access product focusing entirely on publishing high quality proceedings from CIRP conferences, which are relevant to an international audience and cover timely topics.
+ **Procedia Manufacturing (53)** is an open access journal focusing entirely on publishing high quality conference proceedings on all important topics in the field of manufacturing engineering, including but not limited to manufacturing processes, systems and emerging topics in manufacturing.
+ **IFAC-PapersOnLine (30)** publishes all contributions from IFAC meetings (with IFAC being the main sponsor), with all contributions being peer-reviewed according to IFAC rules.

The number in brackets indicates the number of publications that deal with the topic of digital twins. In total, these three journals allow easy and free access of 153 relevant publications and therefore offer an excellent opportunity to examine the topic in more detail.

Figure 2 shows the results of a literature search using the online platform SpringerLink, where researchers can access millions of scientific documents from journals, books, series, protocols, reference works and procedures. The search was done with the restriction where the title contains "digital twin". A total of 136 publications were found, significantly fewer than with ScienceDirect. Out of these 136 publications, 44 are openly accessible, providing another useful source for a detailed study of the subject.

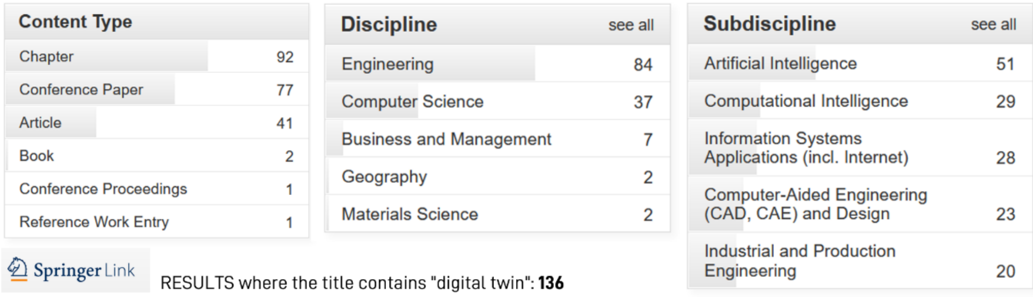

Figure 2: Results of a literature search regarding digital twins using the online platform *SpringerLink*

The aim of this article is to highlight four freely accessible (and in our opinion very good) publications and their essential contents. In detail, the following listed articles will be considered in detail:

+ R. Rosen, G. von Wichert, G. Lo und K. Bettenhausen: About the importance of autonomy and digital twins in the future of manufacturing, International Federation of Automatic Control, p. 567–572, 2015. LINK
+ W. Kritzinger , M. Karner, G. Traar, J. Henjes und W. Sihn: Digital Twin in manufacturing: A categorical literature review and classification, IFAC-PapersOnLine, p. 1016–1022, 2018. LINK
+ E. Negri, L. Fumagallia und M. Macchia: A review of the roles of Digital Twin in CPS-based production systems, in 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM, Modena, Italy, 2017. LINK
+ Q. Qi und F. Tao: Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison, IEEE Access Vol 6, pp. 3585-3593. LINK

In the following three chapters, the present article describes the basic concept of digital twins, the levels of integration and gives an overview about applications of digital twins according to the paper mentioned above.

2 GENERAL CONSIDERATIONS

According to R. Rosen et al. [1] from a simulation perspective, the concept of digital twins is the next wave in modeling, simulation and optimization technology. In their publication, they describe the development over time of simulation as illustrated in **Figure 3.**

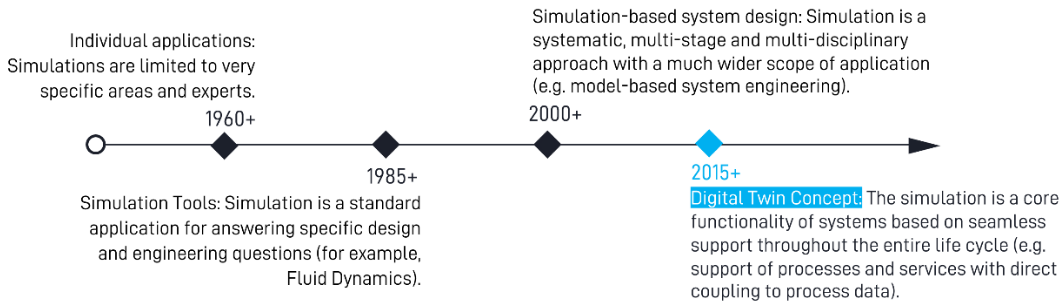

Figure 3: The development of simulation over time according to R. Rosen et al. [1]

R. Rosen et al. [1] summarize the concept of digital twins in the context of Industry 4.0 and CPS as follows: Modularity and autonomy are important issues, as a comprehensive knowledge of the current state of the production system and its own capabilities is required. The collection, storage and processing of all available data available in the production system together with operating conditions are of central importance. However, if not all the necessary data is available, predictions can be made by combining the real data with the simulation models. These are simulations for assistance systems to assist operators and planners with simulation-based predictions. The concept of digital twins makes this possible because all models and data are available in a consistent and well-coordinated environment.

3 DEGREE OF INTEGRATION

In addition to the term digital twin, the relevant literature often uses the terms digital model and digital shadow. A closer look at the publications shows that they differ in the degree of data integration between the physical and the digital counterpart. Some are modeled manually and are not connected to an existing physical object others are fully integrated into real-time data exchange. W. Kritzinger et al. [2] therefore propose a classification according to the degree of data integration.

As a result, a digital model is a digital representation of an existing or planned physical object that does not use any automated data exchange between the physical object and the digital object. A state change of the physical object therefore has no direct effect on the digital object and vice versa (**Figure 4**).

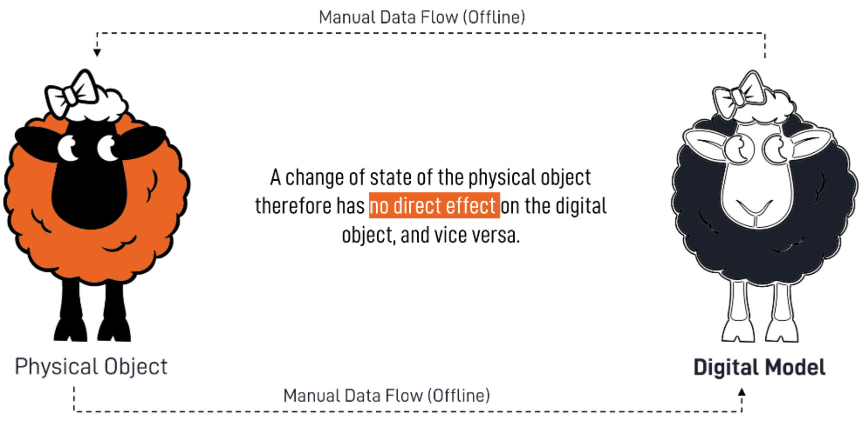

Figure 4: Degree of integration: The digital model

With digital shadows, there is a data flow from the physical object to the digital object. A change of state of the physical object leads to a change of state in the digital object, but not the other way around (**Figure 5**).

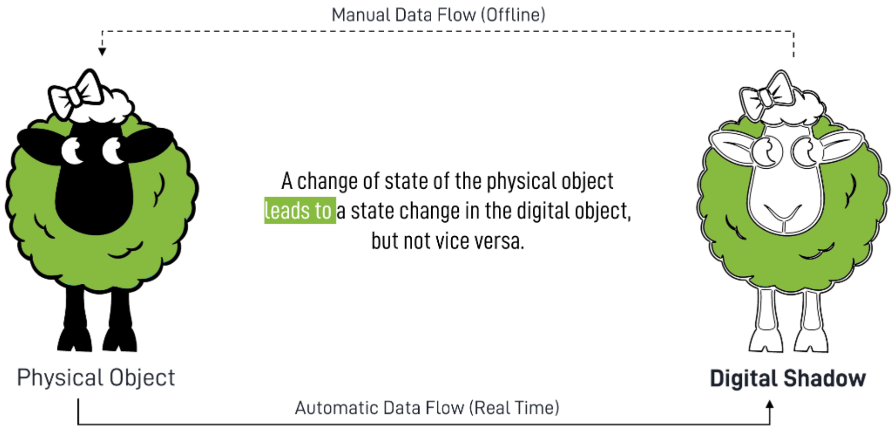

Figure 5: Degree of integration: The digital shadow

If the data flows between an existing physical object and a digital object are fully integrated in both directions, this is referred to as a digital twin. The digital object can also act as a control instance of the physical object. State changes in the digital object can also be caused by other physical or digital objects. A change of state of the physical object leads directly to a change of state of the digital object and vice versa (Figure 6) [2].

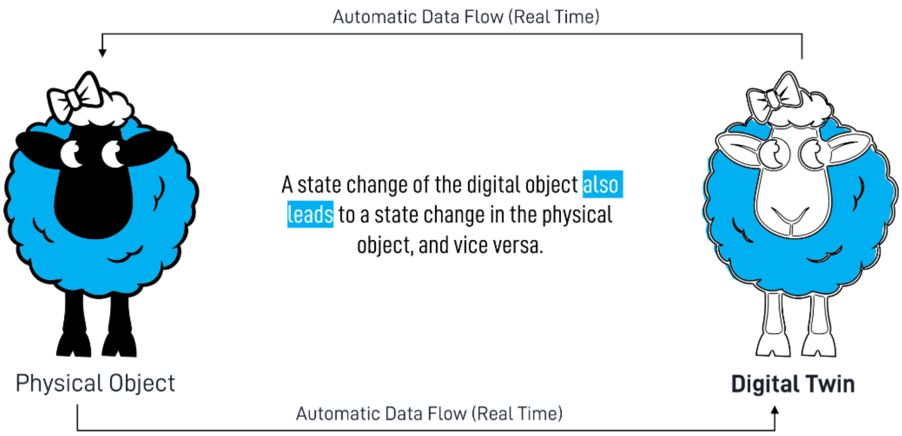

Figure 6: Degree of integration: The digital twin

4 CLARIFICATIONS OF DEFINITIONS

E. Negri et al. [3] conducted a comprehensive literature analysis on the concept of digital twins. From aerospace to manufacturing applications, attempts have been made to clarify the definition and history of the concept of digital twins. The authors show that this is an extremely relevant concept, but many publications do not necessarily use the same definition. The aim of the publication of E. Negri et al. [3] is to clarify the many different definitions of scientific literature. Subsequently, they also try to analyze why and how a concept originally born in the aerospace industry can be beneficial for the manufacturing industry when seen in the context of Industry 4.0. The following is a summary of the publication by E. Negri et al. [3] with regard to the definitions of the digital twin.

The term Digital Twin was first introduced to the public in 2010 in NASA's integrated technology roadmap in Technology Area 11: Modelling, Simulation, Information Technology and Processing [4]:

> *A Digital Twin is an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.*

Although presented for the first time already in 2010, the concept of the digital twin is still very theoretical and conceptual. Real applications in industry are still marginal or not published. It is obvious that the aim of the original definition was to reflect the life span of aircraft by means of a series of integrated sub-models. Only in later research did other aspects emerge (for example the consideration of the life cycle [5] or the use of the digital twin for prognostic and diagnostic activities [6]).

With the work of Rios et al. [7], the definition of the digital twin takes into account a generic product. Initial work in other sectors has already been published. In 2013, the first publications were published reporting on the research of digital twins in the manufacturing industry. In particular, Lee and et al. [8] regarded the digital twin as the virtual counterpart to production resources and not just to the product. This publication was the basis for a debate on the role of the digital twin in advanced manufacturing environments (e.g. Industry 4.0).

The most frequently cited definition is certainly that of E. M. Kraft [9]. In general terms, the digital twin describes the mirroring of a product in its origin. However, the state of the art makes it possible, especially in the manufacturing industry, that processes are also the subject of virtual reproduction. A key aspect of the digital twin is the ability to provide different information in a uniform format. Digital twins are more than pure data; they contain algorithms that describe their real counterpart and decide on measures in the production system on the basis of the process data [10].

For the manufacturing industry, the definition of Garetti et al. [11] is the most appropriate or the most accurate:

> *The digital twin consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration.*

The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behavior of the production system at each life cycle phase in real time [11].

In the course of this chapter a more recent publication by Hendrik van der Valk et al. [21] should also be mentioned. The authors conducted a rigorous and structured literature review and analysis of 233 papers about Digital Twin.As a result, the following central dimensions and features were identified, which can be used excellently for a summary of this chapter:

+ A typical digital twin consists of a bi-directional data link. It processes data and is physically bound to its real-world counterpart.
+ The digital twin is an identical model of a physical system and contains a human-machine interface as well as a machine-to-machine interface. It receives constant updates and processes raw, as well as pre-processed data.
+ The digital twin is often designed after its physical counterpart exists, although the design of it before the physical system exists is recommended. It acquires its data automatically and from multiple data sources.

5 SYSTEMATIC CLASSIFICATION OF APPLICATIONS

A systematic review of the published publications on the concept of the digital twin can also be found in the publication by E. Negri et al. [3].The authors found a total of 26 English-language publications in the Scopus database for the period from 2012 to 2016. These were mainly conference papers (20). It turned out that all references from 2012 and 2013 came from the same conference (53rd and 54th edition of the *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*). It can be deducted that initially only a few research communities worked on the topic. In 2014 there is only one single document, while in 2015 (5 publications) and 2016 (12 publications) the number of publications increases. It is obvious that the scientific literature on this topic is very new. More recent publications cover not only aerospace, but also intelligent manufacturing, especially in the context of Industry 4.0.

The (possible) applications can be summarized on the basis of the available literature, divided into three main use cases, as illustrated in **Figure 7**:

Main Use Case I: Status checks of the product to support maintenance activities.	
Specific application	Number of publications
Monitoring of anomalies, fatigue behavior and crack propagation	7
Monitoring of geometric and plastic deformations	1
MAIN USE CASE II: Digital monitoring of the "life" of the physical entity	
Specific application	Number of publications
Investigation of the long-term behavior and prediction of its performance taking into account environmental conditions	5
Ensuring information continuity in the different phases of the life cycle	2
Virtual commissioning	2
Managing the lifecycle of IoT devices.	1
MAIN USE CASE III: Support decision making through statistic analysis	
Specific application	Number of publications
Optimization of system behavior during the design phase	5
Optimization of the product life cycle. Based on the knowledge of past and present states, it is possible to predict future performance	2

Figure 7: Main application areas of digital twins according to E. Negri et al. [3]

Many of the mentioned use-cases relate to the improvement of maintenance activities. The digital twin as a tool for better predicting failures during the system life cycle based on field data is evident. Another aspect of the concept is the link to simulation, which can be seen in two different ways:

+ The digital twin is a model that represents a system on which different types of simulation can be based.
+ The digital twin as a simulation of the system itself.

In the aerospace industry, the most frequently mentioned simulations replicate the continuous time course of flights (with historical data and maintenance history information). They create huge databases of simulations to understand what the aircraft has experienced and predict future maintenance needs. In the field of robotics, the simulations are mainly carried out for virtual commissioning. This is intended to optimize the control algorithms in the development phase [12, 13].

In manufacturing, the main objective of simulations is to map the complex behavior of the system, taking into account the possible effects of external factors, human interactions and design constraints [1, 14].

In addition to the systematic literature research of Negri et al. [3], with a strong focus on CPS-based production systems, Kritzinger et al. [2] conducted a literature research and classification with regard to 4 categories. The categorization was carried out based on type, degree of integration, focus area (applications) and technology. **Figure 8** shows the results of this research summarized as pie charts.

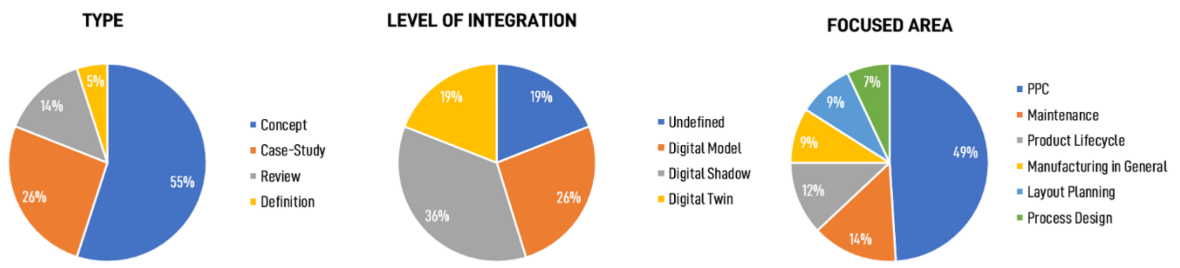

Figure 8: Results of the categorized literature research by Kritzinger et al. [2].

The authors summarize their results as follows: The majority (55 %) of the literature examined could be classified as concept, which indicates that research is still in its infancy. Many researchers are currently beginning to derive suitable concepts as a first step towards implementing the digital twin in practice. 26 % of the publications analyzed were identified as case studies. The main focus of these contributions is on describing the case studies themselves and discussing their findings.

Looking at the degree of integration, the digital shadow accounts for the largest share, followed by the digital model. Although the majority of publications use the term digital twin, only 19 % of them actually describe a digital twin with bidirectional data communication.

In the focus area (applications) category, most publications focus on production planning and control, followed by maintenance, especially condition-based maintenance. Product life-cycle management was an original idea of digitization within product development, with digital models and shadows being used most. Here, however, it is also possible to virtually test the behavior of the product to be developed and to iterate certain parameters in order to optimize its performance and producibility. Some of the publications do not focus on a specific area of manufacturing. They deal with the digital twin in a broader sense and are therefore classified as *general manufacturing*.

A combined analysis of the two categories type and degree of integration allows a more detailed consideration and is shown in **Figure 9**.

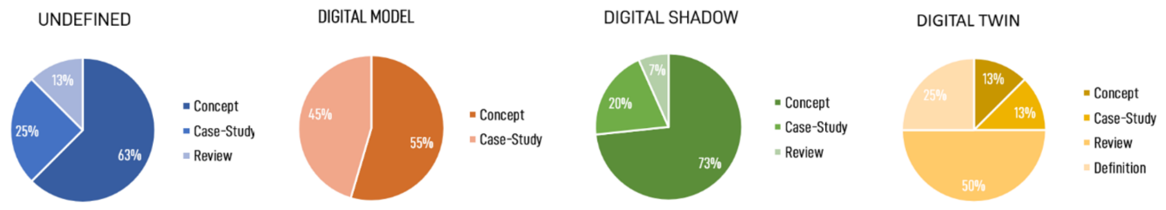

Figure 9: Combined consideration of type and degree of integration according to Kritzinger et al. [2].

Leaving out the undefined degree of integration shows that the relative number of case studies decreases with increasing degree of integration (45 % digital model, 20 % digital shadow and 13 % digital twin). The figure also shows that there are already many concept publications for the digital shadow (75 %), also for the digital model (55 %), but not for the digital twin. Here, the majority of publications are of the research type (55 %).

A similar classification regarding applications for digital twins was done by Q. Qi und F. Tao [15]:

+ **Digital twin-based production design:** Here the digital twin can enable the iterative optimization of the design scheme. The designers can thus improve the design models to achieve a personalized product design. In addition, virtual verification can be used to quickly and easily predict and verify product functions, behavior, structures and manufacturability [16]. By using the digital twin, a design flaw can be accurately found in the virtual world. This allows rapid changes to be made, improving the design and avoiding lengthy reviews and testing.
+ **Smart manufacturing using digital twins:** The entire production process, from raw material input to the end product, is controlled and optimized by the digital twin. The virtual workshop or factory includes the geometric and physical models of operators, materials, equipment, tools, environment, etc., as well as behaviors, rules, dynamics models and others [17]. Before the products are manufactured, production resources and capacities are allocated, and the production plan defined. The virtual factory simulates and evaluates the various manufacturing strategies and plans until satisfactory planning is confirmed. In the actual manufacturing phase, monitoring and adjustment of the manufacturing process is realized in real time through virtual-physical interaction and iteration. The virtual models are updated based on data from the physical world to keep abreast of changes. Any problems can be identified, and the optimal solution is developed by simulation in the virtual world. Based on simulations in the virtual factory, the manufacturing process is adapted to achieve optimal manufacturing (e.g. accuracy, stability, high efficiency and product quality).
+ **The digital twin in product monitoring:** Here, a virtual model of the product is created. The digital twin of the product is constantly linked to the real product to provide value added services [18]. This means that the product being used is monitored in real time as the digital twin continuously records product usage status data and accesses environmental data and operating parameters. This allows users to stay up to date with the latest product status. Subsequently, the virtual model can simulate the operating conditions of a product in different environments and thus analyze the impact of

different environmental parameters. It is also possible to analyze the operating behavior in terms of service life or performance. Another use case is the prediction of lifespan based on the real-time data of the physical product and history data[19].

+ **Digital twins as key components for maintenance and repair:** Here, the digital twin is intended to prevent sudden downtimes through proactive maintenance. This proactive maintenance is triggered based on the prediction of the condition, the remaining service life and errors. When an error occurs, the virtual model of the product visually diagnoses and analyzes the error. Maintenance personnel are shown the location of the faulty part and the cause of the fault [20]. Maintenance strategies are performed in the virtual world based on virtual reality and augmented reality. This is possible because the mechanical structure of the parts and the coupling between them are faithfully reproduced by the virtual models. Thus, it can be determined whether the strategies are effective, executable and optimal. In addition, the data from the various phases of the product life cycle are collected and inherited in order to contribute to the innovation of the next generation product.

6 SUMMARY

A very positive fact is that there are a large number of journals that provide free access to science-based studies on the concept of digital twins. This easy and free access to relevant publications dealing with digital twins, and therefore offer a great opportunity to study the topic in more detail. Based on freely available publications the present article described the basic concept of digital twins, the levels of integration and gave an overview about applications of digital twins according to the paper mentioned above. The findings can be summarized as follows:

+ A digital twin is a virtual representation of a production system with different simulations which are characterized by synchronization between the virtual and the real system. The real-time data acquisition and processing, the coupling with so-called smart devices as well as mathematical models play a decisive role.
+ In Industry 4.0 manufacturing systems, the current task is to use these functions to predict and optimize the behavior of the production system in real time at every life cycle phase.
+ The available literature mainly consists of concept papers with a focus on production planning. Some case studies are already beginning to emerge and the digital twin in manufacturing is gaining more and more attention. Some researchers see a need for further research in the development of optimization and simulation methods. Others see data connectivity as the main problem. There is a consensus that further research is needed on the conceptual basis. The digital twin offers enormous benefits for industrial applications, but there is still a lack of case studies that apply the concepts in practice.
+ Digital twin applications include product design, intelligent manufacturing, component monitoring, and maintenance and repair. Only 9 % of the projects observed as a whole deal with intelligent manufacturing using digital twins. However, the majority of this percentage is currently still in the concept phase.

At qoncept dx we see the great benefit of digital twins in the supervision, control and optimization of metallurgical processes in real time. A subsequent article will describe how we combine fundamental-based modeling with artificial intelligence models (data-driven modeling).

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