Digital Twins for Real-time Data Analysis in Industrie 4.0: Pathways to Maturity

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Abstract: Digital twins are virtual copies of production systems' physical components. In Industrie 4.0, they represent a promising opportunity for analysing production data in real-time and contribute to improved production planning and control. However, development of digital twins is challenging for companies due to missing guidance. In this research paper, we identify four maturity levels for digital twins for real-time data analysis based on a structured literature review and a market analysis that resulted in a total of 82 analysed contributions. The results are evaluated through a qualitative interview with four experts from academia and practice. Manufacturing companies can use the maturity levels for self-assessment and as a guideline. Future research can use the maturity levels for integration into holistic maturity models.

1 INTRODUCTION

Industrie 4.0 describes the vision of digitalized production in which decision-makers can be provided with analysis results in real-time (Kagermann, Wahlster, & Helbig, 2013). Digital twins represent a core component for fulfilling this vision (Kuhn, 2017). A digital twin describes the virtual representation of a physical object. The virtual representation allows analysis and simulation at any time, even already before the existence of the real object. To implement digital twins, all characteristics of the physical object have to be known (Stark & Damerau, 2019). This includes current as well as possible future states.

Using digital twins can have significant advantages for real-time analysis in production. E.g., detailed simulations can predict production anomalies and instantly model their consequences (Riedelsheimer, Lünnemann, Wehking, & Dorfhuber, 2020). Current states of production can provide for better planning of future production orders by means of the digital twin and thus increase overall production efficiency.

However, the requirements for a holistic digital representation of production are high (Riedelsheimer et al., 2020). Above all, it is demanding when companies want to digitally map flexibly combinable production machines including their production environments. The integration of upstream and downstream processes, such as marketing and sales, makes the implementation even more challenging (Kaufmann & Servatius, 2020). Yet, the integration and real-time analysis of data from cross-departmental processes may lead to competitive advantages by enabling predictive capabilities and seamless workflows (Liu, Meyendorf, & Mrad, 2018). Difficulties that arise in the implementation of digital twins essentially relate to the provision of data in real-time and the competence to analyse this data in a target-oriented manner (Kunath & Winkler, 2018). These difficulties can lead to inertia in the adoption and implementation of digital twins for real-time data analysis. Therefore, companies need guidance to assess the current state of their digital twin implementation and to know along which dimensions they should continue their development (Riedelsheimer et al., 2020). Maturity levels specific to digital twins with the purpose of real-time data analysis may provide manufacturing companies with this guidance.

On this basis, we formulate the following research question: *How can maturity levels be designed for digital twins used for real-time data analysis?* To answer this research question, we conducted a structured literature review based on Vom Brocke et al. (2015) as well as a market analysis of production companies.

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The remainder of our research contribution structures as follows. Section two details the methodological approach. Section three shows characteristics of the found contributions. Section four presents the identified maturity levels. Methodology and results of the qualitative evaluation are outlined in section five. Lastly, sections six and seven include a discussion, starting points for future research and a conclusion.

2 METHODOLOGY

This chapter aims to present the methodological procedure of the structured literature review in scientific data bases and the market analysis based on information from industrial production companies. Regarding the structured literature review, we followed the procedure proposed by Vom Brocke et al. (2015). Relevant scientific literature was searched in the databases *Google Scholar, IEEE Xplore, Science Direct, Scopus* and *Springer Link*. Table 1 contains the search string combinations.

Table 1: Alternative search string combinations.

OR	Digitaler Zwilling Digital Twin
AND	
OR	Real-time data analysis Streaming data analysis
AND	
OR	Industrie 4.0 Industry 4.0 Smart factory Smart manufacturing

On top are the alternatively used terms of the digital twin in German and English. The German variant was included, because all participants in the research project are native speakers. The search terms in the middle refer to real-time analytical processes. Below, the alternative equivalents for the German "Industrie 4.0" are shown. The equivalents were iteratively determined while going through literature and included as search strings to expand the search space. Initially, only two terms were combined. Subsequently, terms from all three sections shown in Table 1 were used.

We first used a keyword search, then forward and backward search. The search was restricted to publications from after 2015 as a Google Trends analysis shows a tendency of increased attention in literature on digital twins from 2015 onwards. Only literature written in German or English was considered. The literature identified in the search was selected by two inclusion and two exclusion criteria. Inclusion criteria were, first, that the search terms "Digitaler Zwilling" or "Digital Twin" were mentioned in title, introduction or keywords. Secondly, publications were included in which the concept of the digital twin was clarified by background information or clear descriptions even without mentioning the terms explicitly. Publications whose information was insufficient to contribute to answering the research question were excluded. In addition, publications that were purely theoretical and did not show any reference to an entrepreneurial context were excluded. The validity of one criterion was decisive for inclusion or rejection. If publications fulfilled at least one inclusion criterion and at least one exclusion criterion, an individual decision was made in each case. After application of the criteria and exclusion of duplicates, 44 results were obtained.

Additionally, we performed a market research. We searched the keywords from Table 1 using *Google*. The goal was to include current practical applications of the digital twin in industrial practice. To this end, we focused on press releases of industrial manufacturing companies covering descriptions of implementations, implementation recommendations and experience with the topic. Again, we restricted our search to publications from 2015 or later. The inclusion and exclusion criteria were the same as in the structured literature review, except for the second exclusion criterion as purely theoretical results were not expectable. This search resulted in 38 practical contributions.

This research paper does not aim to present a ready-made maturity model, but to identify stages of such a model in order to show pathways to maturity. However, we still adhere to the eight requirements for the development of a maturity model given by Becker et al. (2009).

3 FINDINGS

This chapter aims to present further information on the references found by structured literature review and market analysis. Table 4 shows the kinds of contributions in the scientific literature. Most of the publications make a practical contribution. In fact, only two publications target a purely academic audience. 15 publications contribute to both academia and practice. Case study creation or analysis is the most frequently found methodology in the scientific references.

Table 2: Kinds of contributions of scientific references.

Contribution	Type	Methodology	No.
Academic	Book	Literature review	1
	Journal	Literature review	1
Practical	Book	Case study	6
		Literature review	1
		No specific	3
		Review	4
	Conference	Case study	6
		Literature review	1
		Review	2
		Qualitative survey	1
	Journal	Case study	1
		Literature review	1
		Review	1
Both	Conference	Design science	1
		Literature review	4
		Review	1
	Journal	Literature review	2
		No specific	4
		Review	3

Table 3: Distribution of scientific references by industry and purpose.

Industry	Purpose	No.
Engineering	Analyse characteristics	2
	Analyse different applications	1
Logistics	Analyse characteristics	1
	Analyse different applications	2
	Creation of digital twins	3
No specific	Analyse characteristics	10
	Analyse different applications	7
	Explore potentials	3

Table 3 presents the industries and purposes the scientific publications refer to. Only engineering and logistics are explicitly mentioned, most publications do not name a specific industry. These publications are grouped as “no specific” in the first column. The analysis of characteristics of digital twins is the most frequent purpose among the identified scientific references. The second most frequent purpose is the analysis of applications. These scientific references refer to real or conceptual implementations of the digital twin and outline its disadvantages and advantages. Ten scientific publications have other purposes. Examples are the creation of frameworks or generic requirements for the implementation of digital twins (Azarian, Yu, Solvang, & Shu, 2020). Ten scientific publications have other purposes. Examples are the creation of frameworks or generic requirements for the implementation of digital twins (ibid.). Table 4 presents the practical contributions’ industries and purposes. Most of these refer to quality and efficiency assessment as well as advancements in digitalization when implementing the digital twin or specific features to obtain advantages of real-time data analysis.

Table 4: Distribution of practical references by industry and purpose.

Industry	Purpose	No.
Automotive	Digitalization	9
	Planning	9
	Quality and efficiency assessment	6
	Sales	4
	Training	2
Industrial engineering	Quality and efficiency assessment	6
Other	Digitalization	1
	Sales	1

4 PATHWAYS TO MATURITY

Based on our findings in scientific literature and practical contributions, we identified three dimensions that enable the differentiation of four maturity levels. The levels including their dimensions reoccurred in the referenced publications and were identified in an iterative process (Becker et al., 2009). The first dimension refers to real-time data continuity and consistency. The second dimension relates to companies’ analytical capabilities for real-time validation and quality assessment in production. The third dimension considers the integration of stakeholders, which include machines and humans directly involved in production steps or upstream or downstream processes. Figure 1 relates the dimensions and shows the four distinguishable maturity levels. These are sequentially dependent, so that later levels include all characteristics of previous levels.

In the **first maturity level**, data transparency in a consistent real-time data base is initially created in isolated production aspects. Continuous real-time data collection during the execution of single work steps gradually increases data transparency. Step by step, a uniform data basis is created that is suitable for real-time data analysis. This requires consistent data models before analysis, since real-time analysis is not suitable for separate data organization after or parallel to analysis (Stahmann & Rieger, 2021). Regarding the third dimension, the focus restricts to company

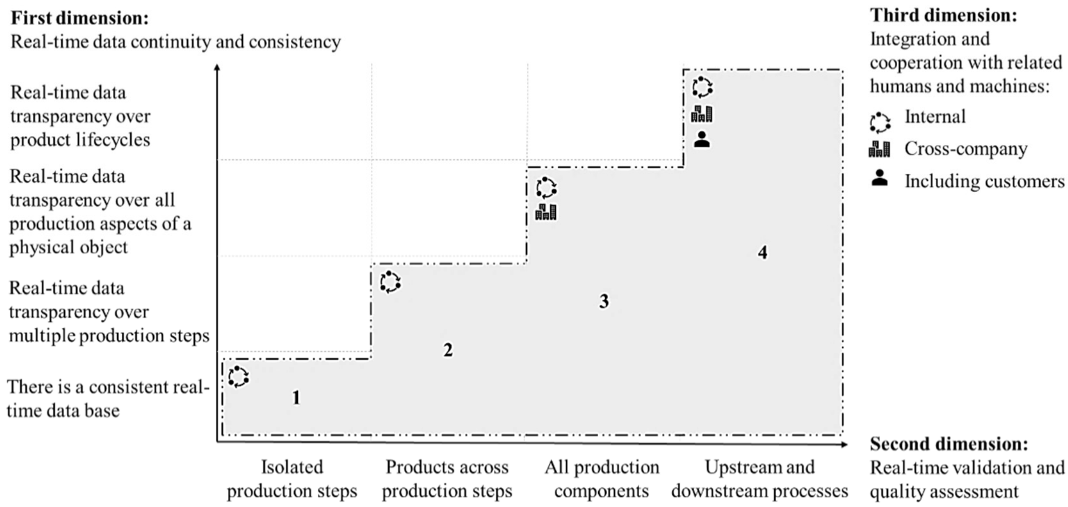

Figure 1: Maturity levels identified through structured literature review and market analysis.

internal processes. Adamenko et al. (2020) explain the trade-off between a more and more detailed virtual representation of a physical object and the increasing complexity in data organization. The authors examine the concept of a data-based digital twin, which uses sensor data of a physical object and enables specific analyses.

Ait-Alla et al. (2019) intend to observe the effects of deploying different numbers of sensors to machines to create digital twins in different detail levels. The authors can identify differences in the speed of data communication and productivity depending on the progress of virtualization of isolated production steps. In line with our first maturity level, the degree of data acquisition from a physical source thus progresses step by step. The major benefit of this maturity level is the continuous creation of a real-time data base, which enables the virtual simulation of physical processes. On the other hand, this may require to fundamentally change previous data structures.

Redelinghuys et al. (2020) create a reference architecture for digital twins including physical objects and their holistic virtualizations. Using a case study, the authors demonstrate how the reference architecture is suitable for real-time simulation and anomaly detection based on the virtualization of individual production steps.

The **second maturity level** in the dimension real-time data continuity and consistency comprises transparency over multiple production steps. This transparency requires a consistent real-time data base covering data from dependent production steps. The focus of data management thus shifts from continuous database creation of isolated aspects to the integration of related steps in the production process. In the third dimension, the second maturity level refers to internal company processes like the first maturity level.

Adamenko et al. (2020) analyse and compare instantiations of the digital twins to understand application potentials and design alternatives. As in our second maturity level, the authors find that models of several interrelated aspects of production must be combined virtually to provide a proper representation of the physical equivalent.

Also, the digital recording and transparency creation of products across production steps enables creation of key figures in real-time (Daimler AG, 2020). Aggregated key figures may provide a view of several products in different steps, more detailed key figures can address individual products and their production status.

RFID chips may simplify the real-time localization of individual products and their components across production steps (BMW Group, 2020). This means that information on the progress of all products, involved machine components or employees is available at all times. By evaluating virtual production processes, error-prone and inefficient processes can be identified (Audi, 2019). Solutions for these processes can then be developed and tested directly in the virtual production environment. This means that the entire production process can be optimized before cost-intensive changes (Adler & Masik, 2020).

This maturity level's benefit is the high level of detail of such an implementation of a digital twin, which can e.g. be used for comprehensive real-time simulations of physical processes. A major hurdle in achieving this maturity level resides in the continuous integration of the production steps real-time data (Adamenko et al., 2020).

In the first dimension, the **third maturity level** covers real-time data transparency overall production aspects of a physical object. The virtualization is holistic and does not only include isolated aspects. Accordingly, the second dimension also includes validation and quality assessment of all production components involved. The availability of integrated production data enables leveraging more profound data analysis and usage (Tao et al., 2019). As production may include components delivered by suppliers or the provision of own products for subsequent manufacturing, the third dimension also includes other companies (Reisewitz, 2018). Digital twins that are separated in partial models may constitute the data basis for cross-company cooperation (Tao, Qi, Liu, & Kusiak, 2018). E.g., the supplier of semi-manufactured production components may deliver specific characteristics virtually such as weight or quality to facilitate subsequent production (Reisewitz, 2018). Real-time production data used for simulation in alternative production process orders and facility layouts may reduce costs and improve production efficiency. The subdivision of digital twins does not only hold advantages for cross-company cooperation, but also internally. Depending on the intention, digital twins that depict all details of a physical object can be combined. The creation of a large, non-subdivisible digital twin would be costly, the use e.g. for simulations might result in overhead calculations. According to Adamenko et al. (2020), the level of detail encompassed by subdivided digital twins leads to better simulations for checking machine and product conditions in real-time. The detailed simulation can make the implementation of real prototypes unnecessary. Slot et al. (2020) propose a framework to systematize and simplify the integration of different digital twins. The framework provides guidelines for the integration of digital twins to networks, e.g. for real-time analysis.

Furthermore, another potential of the digital twin in maturity level three is employee training on the basis of real-time production data (Audi, 2020; Porsche, 2018). Simulation of different production situations may increase efficiency. Also, employees' safety may be increased due to virtual training as potentially dangerous situations may be trained during simulation.

The **fourth maturity level** refers to real-time data transparency over product lifecycles in the first dimension. This extends the third maturity level by covering all aspects of physical objects including changes over time. Accordingly, the second dimension also includes upstream and downstream production processes. The fourth maturity level therefore integrates internal and cross-company processes as well as customers. A major benefit of achieving this maturity level is that customers can be integrated both before and after production to meet individualized demand. Before production, the virtual twin of the product can be used to present production alternatives to the customer, e.g. using virtual reality (Porsche, 2018). After sale of a product, customer usage data can be transmitted to the manufacturer for real-time analysis. User behavior can form the basis for follow-up offers or changes to the future product (Schleich, Anwer, Mathieu, & Wartzack). Negative effects of strong customer integration may be the dependence on individual customer behavior and the loss of know-how regarding own innovative ideas for product and service development (Gassmann, Kausch & Enkel, 2010).

Covering entire lifecycles, the digital twin can also generate benefits in the area of sustainability (Riedelsheimer et al., 2020). It can form the basis for defining ecological indicators, such as overall energy demand or resource efficiency through virtualized planning and control. E.g., environmentally harmful emissions of each production component can also be recorded and analysed.

5 EVALUATION

This chapter outlines methodology and results of the qualitative interviews conducted with experts from industry and academia.

5.1 Methodology

To evaluate and broaden our findings, interviews with four experts were conducted. From industry, an expert from an internationally operating supplier in pneumatic automation and an expert from an international automobile manufacturer were interviewed. The scientific perspective on the digital twin was covered by an expert from an institute for applied sciences and an expert from a business-related research institution. The interviews were electronically recorded with the consent of the interviewees. The interviews lasted about 41 minutes on average. They were conducted in German, as all participants were native speakers.

The basis for the expert interviews was a semi-structured questionnaire that built on the steps of the three dimensions shown in Figure 1. We did not explicitly present the identified maturity levels, so that answers were not restricted to our findings.

Rather, we took an explorative perspective during analysis of the answers following Bell et al. (2019).

5.2 Results

Table 5 has the purpose to summarize the experts' main statements on the dimensions identified in chapter 4. The items listed in Table 5 group into confirmations or emphasis of the findings from literature and market research or the addition of further factors that impact the identified maturity levels.

Table 5: Results from expert interviews in relation to dimensions.

	Results from expert interviews
First dimension:	✓ Uniform database across companies
	✓ Virtual mapping of aspects of physical objects
	+ Use of digital twin for employee knowledge preservation
	+ Insufficient employee know-how
	+ Lack of standardization in creating real-time data continuity and consistency
	! Data granularity needs to fit the digital twin's purpose
Second dimension:	✓ Digital twin used as basis for validation
	✓ Production feasibility assessment of individual customer demand by simulation
	✓ Comparison of as-is and to-be production characteristics to detect production anomalies
	✓ Potential for predictive maintenance
	+ Lacking trust in simulation results
	+ Difficulty identifying cost-benefit ratio
	! Possibility of simulation of various aspects
Third dimension:	✓ Cross-company cooperation to enhance efficiency
	✓ Integration of customers' individual demand
	+ Data protection issues
	+ General trust issued regarding cooperation
	+ added, ✓ confirmed, ! stressed

Relating the experts' answers to the dimensions from chapter 4, a connection between the first and third dimension can be supported. Cross-company cooperation can be made more efficient through digital twins.

From a scientific perspective in particular, the digital mapping of all relevant areas of an object in the real world for real-time data analysis could be supported.

Attempts are made to map the entire lifecycle of a product or machine using digital twins, which supports the connection of all three dimensions. In practice, the digital twin allows the consumer to be integrated more closely into product development. By collecting real-time consumer data, market research can be conducted in a more targeted manner.

Besides support of our findings, challenges of using the digital twin in Industrie 4.0 were addressed during the expert interviews. Regarding the third dimension, experts added data protection and lack of mutual trust between cooperating companies as particular challenges for the establishment of digital twins. Moreover, the acceptance of digital twins in business practice is a major hurdle. Companies often lack the necessary trust in the simulation results of the digital twins to follow the proposed recommendations for action. The lack of trust in the digital twin also leads to problems when determining its cost-benefit ratio, which may prevent their development. Furthermore, there is often a lack of functional examples to illustrate the added value of improving or expanding existing applications. Therefore, empirical values on the use of digital twins for real-time analysis would be beneficial for determining the cost-benefit ratio.

According to expert interviews, small and medium sized companies in particular encounter obstacles when introducing digital twins. Insufficient knowledge about their use and creation of real-time data continuity and consistency were identified as challenges. For large companies, the challenge lies more in identifying meaningful areas of application. From both a business and a scientific perspective, a lack of standardization in relation to the digital twin can be identified in conjunction with insufficient know-how. The expert interviews reveal that the standardization challenges are primarily taking place in the first dimension as there is no comprehensive standardization covering all aspects of a continuous, consistent real-time data base for digital twins.

6 DISCUSSION

This chapter aims to critically reflect our study and outline starting points for future research.

Despite adherence to methodological guidelines, procedure and results of this research paper are not free from limitations. Regarding the systematic literature review, there is no guarantee that relevant research publications were not included due to the selection of search strings, databases, and exclusion of publications prior to 2015. In addition, the application of exclusion criteria is subject to the judgment of the researcher. 38 sources from industry that served as basis for deriving the maturity levels are not from scientific databases. The sources are not free of economic advertising, which had to be reduced to objective facts. Moreover, several publications identified with the help of scientific databases come from conferences, only 13 were published in journals. This may indicate that the topic has a low level of scientific maturity. Future research might increase the topic's scientific maturity by investigating long-term effects and strategies for implementing results regarding digital twins in data analysis from scientific reviews (Lim, Zheng, & Chen, 2020; Tao et al.; Tao et al., 2019; Tao & Zhang, 2017).

The derived maturity levels are generic. In individual cases, this can make the concrete use of the maturity levels more difficult. Also, it seems recommendable to start implementing the levels subsequently in an iterative process. This is due to the effort required to change existing data organization and analysis practices in companies.

In addition, the expert interviews are not generalizable, as only four experts were interviewed. Instead, the expert interviews are intended to serve as an initial critical reflection on the literature review's findings. Future research may discuss these findings in more depth in a qualitative study with more participants from different perspectives.

7 CONCLUSION

The digital twin is a promising concept for implementing real-time data analytics in Industrie 4.0 production environments. Creating transparency about current aspects of production holds potential for controlling production as well as integrating it with related processes and stakeholders. However, implementing digital twins for real-time data analysis requires consistent, continuous data collection and preparation as well as analytical and integrative capabilities for processing permanent data streams in production as well as upstream and downstream processes. The joint development and overarching integration of these capabilities is complex and requires guidance.

A structured review of scientific literature and practical contributions resulted in 44 scientific sources and 38 references from industry practice. On this basis, this paper contributes with the identification of four maturity levels for digital twins for real-time data analysis. The result was evaluated and extended with four qualitative interviews with experts from industry and academia based on a semi-structured questionnaire. The evaluation mainly substantiated our findings and added practical challenges regarding the implementation of digital twins.

Our paper contributes to research and practice. Other scholars can e.g. contribute on the basis of quantitative surveys of the states of digital twins for real-time analysis in manufacturing companies. A further differentiation of the identified maturity levels is also possible through a broader literature research, which may include factors that are relevant for production planning and control, such as reporting with the help of digital twins. In addition, future research can integrate the maturity levels into a broader maturity model for the digitalization of production. Practitioners can apply the results and also extend them on the basis of concrete use cases.

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