Digital Twin for Verification and Validation of Industrial Automation Systems – a Survey

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***Abstract*—Digital Twins will change how systems and products are engineered and operated. Individual virtual representations of assets help to develop, maintain and change single components or whole factories. Aerospace engineering, product design and intelligent manufacturing are hot spots for the use of Digital Twins. Simultaneously, globalized markets lead to a growing awareness of dependability and quality, which increases the importance of verification and validation. The Digital Twin could prove to be key enabler for efficient verification and validation processes. This paper presents the results of the literature review of approaches that use Digital Twins for verification and validation purposes. Many solutions have been found for a wide range of challenges in various fields of application. This survey discusses the underlying methods and the elements of Digital Twins already in use. Most research approaches focus on simulations and three methodological clusters of approaches sharing similar ideas were identified.**

Keywords— Digital Twin, verification, validation, testing

I. Introduction

Products and systems today are becoming increasingly intelligent and autonomous and require new approaches to ensure reliability and safety [1]. To guarantee these properties, new, sophisticated approaches to verification and validation are required. Digital Twins promise to facilitate product and system engineering as well as operation [2]. There are many ideas on what a Digital Twin is. As analyzed in detail in [2], most definitions share the basic idea that a Digital Twin enables asset-specific storage and provision of models. Developers, testers and operators can then use these models for their own application purposes.

Central, asset-individual storage of up-to-date models helps enormously with verification and validation. In addition, the increasing availability of simulations with Digital Twins opens up new possibilities for checking assumptions in parallel to operation. Therefore, Digital Twins are a promising new technology for designing and operating reliable systems. The above considerations for using the Digital Twin for verification and validation purposes are mentioned in many different papers about the Digital Twin [3–5], especially in the field of manufacturing systems and factory automation [2, 6–9]. However, a discussion of existing approaches is lacking. In order to support the coordination of research, this paper analyses publications in the field of using the Digital Twin for verification and validation. Furthermore, this survey is intended to help practitioners to find the approaches that are relevant for them. The aim of this paper is to provide an overview of the state-of-the-art in using the Digital Twin for verification and validation.

The remainder of this paper is structured as follows: Section II gives an overview about central terms and basics on the topic Digital Twin. Next, the survey goals in the form of research questions as well as the methodology of the literature search are explained in Section III. Afterwards all analyzed publications are presented in Section IV whereas Section V holds the discussion of all research questions. Finally, a conclusion and an outlook follow.

II. Basics

A. *Verification, validation and testing*

According to ISO/IEC/IEEE 24765, verification and validation (V&V) is the "process of determining whether the requirements for a system or component are complete and correct, the products of each development phase fulfill the requirements (…), and the final system or component complies with specified requirements" [10, p. 504]. Verification ensures that "the system has been built right" [10, p. 503]. Validation addresses the question whether "the right system has been built" [10, p. 499]. In common parlance, testing is often used as an analogy for verification and validation However, testing is rather a method to falsify assumptions and hence part of verification and validation. According to ISO/IEC 25051, test is an "activity in which a system or component is executed under specified conditions, the results are observed or recorded, and an evaluation is made of some aspect of the system or component" [11, p. 4].

Verification and validation are engineering tasks during development. In systems with high flexibility requirements, the boundaries between initial development, operation and continuous improvement become blurred. The Digital Twin is a technology to improve the continuity of engineering during the entire asset life cycle [2]. As discussed in Section V.C, the approaches found can be divided into approaches for verification and validation during development as well as parallel to operation.

B. *What is a Digital Twin?*

The Digital Twin is a digital replica of a physical system and able to mirror its static and dynamic characteristics. It contains all models and data of the physical systems and is at all times in sync with the physical system [12]. Meaning, if changes happen in the physical world, the models are automatically updated. Some of those models are executable, meaning they can be simulated. Various, slightly different definitions exist of the Digital Twin, an overview is given in [2]. But all definitions contain the three parts: models and data, being in sync and simulation capabilities [2]. Closely related to the concepts of Digital Twin is the so-called asset administration shell [13]. The administration shell has high relevance for manufacturing systems and can be seen as a formal, standards-based Digital Twin for Industry 4.0. The administration shell is one possibility to realize a Digital Twin.

Moreover, [2] gives a detailed list of necessary elements of a Digital Twin in form of an architecture for the Digital Twin. For this architecture, several already existing architectures were compared and all necessary elements were extracted:

- **ID:** Unique ID of the asset and its Digital Twin
- **Models and corresponding interfaces to tools:** All models of the Digital Twin in their respective tools as well as interfaces to tools for accessing the models
- **Version Management:** Contains the historic models of the Digital Twin and their relations
- **Operation Data:** All accumulated data
- **Organization and technical data:** Contains information and documents on the physical asset, like design layouts, maintenance reports, etc.
- **Relations to other Digital Twins:** Contains information to which other physical systems the represented asset is connected
- **Co-Simulation interface:** Interface for communication with other Digital Twins to enable a holistic simulation
- **Interface for the synchronization of models and relations:** Interface to keep the Digital Twin in sync with the physical system
- **Interface for data-acquisition:** Interface for obtaining operation data

Additionally to the Digital Twin, [2] also defines an Intelligent Digital Twin. The Intelligent Digital Twin extends the Digital Twin by the following elements:

- **Algorithms for the Intelligent Digital Twin:** Algorithms to process the operation data and analyses simulation results to optimize, maintain, etc. the physical asset
- **Digital Twin model comprehension:** To run algorithms on the simulations and models an understanding of what the models contain is needed
- **Services:** Interact with other Digital Twins or systems
- **Feedback interface:** An interface to transfer the data generated by the algorithms back to physical system

Therefore, the Intelligent Digital Twin is a very sophisticated tool, which can be leveraged for testing, verification and validation. Each Digital-Twin-based application uses normally only a subset of the described elements. Most of the approaches addressing verification and validation use as discussed in Section V.A only a very small subset.

III. Goals and Methodology

The goal of this survey is to investigate how the Digital Twin is used for verification and validation. Ranging from the validation of non-functional properties to the verification of safety-critical requirements, verification and validation is a very broad topic. Based on the above goal, we raise the following three research questions (RQ):

RQ 1: Which elements of the Digital Twin are essential for verification and validation purposes and where is unexploited potential? For all approaches it was examined which of the in Section II.B mentioned elements of the Digital Twin are used. The answer to this question therefore allows an estimation of which approaches could be realized with an already existing Digital Twin. Furthermore, the discussion in Section V.A shows that not the full potential of Digital Twins is used for verification and validation.

RQ 2: To what extent are approaches similar and is it possible to determine methodological clusters? With the help of these clusters, an overview on the different mindsets of using the Digital Twin for verification and validation is provided.

RQ 3: In which application domains is the Digital Twin used so far for verification and validation? For this purpose, it was analyzed whether within the examined publications an application area was addressed explicitly or by naming examples. By examining application domains, approaches become visible that address the same domain or deal with similar problems in adjacent domains.

There are other surveys in this field addressing the state of the art of Digital Twin [14–17] and the verification and validation of cyber-physical systems [18–21]. However, there is a survey gap regarding verification and validation approaches that make use of a Digital Twin. This gap and the unanswered research questions are discussed in this paper. In order to answer the research questions, a literature search was conducted taking into account the methodology proposed in [22]. For this purpose, a search was made on scholar.google.de with the following six search terms without additional search operators or search options: *verification Digital Twin*, *validation Digital Twin*, *Digital Twin dependability*, *Digital Twin safety*, *Digital Twin test*, *asset administration shell verification validation test*. The extension of the initial two search terms *verification Digital Twin* and *validation Digital Twin* was carried out, as the additional keywords test, dependability and safety are closely related to and often used in analogy to the keywords verification and validation.

The search term *Digital Twin test* generates the highest number of hits, with google scholar around 253k. *Digital Twin safety* follows, around 94k. *Validation Digital Twin* and *verification Digital Twin* are close to each other with 66k respectively 56k hits with google scholar. The rather specific search term *asset administration shell verification validation test* was chosen because Digital Twin and the asset administration shell are in parts closely related thematically.

With google scholar, it generated around 20k hits, however, no approach for using it for verification and validation purposes was identified. The fewest hits were obtained with the search term *Digital Twin dependability*, around 4,7k hits with google scholar. Nevertheless, *Digital Twin dependability* proved to be a very important search term since it produced less false positive hits compared to the other queries.

The main difficulty in the literature research was to efficiently identify and sort out false positives for further consideration. About 900 publications were analyzed, only a fraction of the search hits. This represents a limitation to our research as relevant publications might stayed undetected. The literature search and analysis method used consists of two steps. First, the title and abstract found with a certain search term were analyzed to sort out most of the false positives. If more than 50 consecutive false positives were found, the search with that search term was aborted. In a second step, two or more of the authors read the full-texts of the remaining 135 papers to mitigate researcher bias. The main contribution was made by the first two authors. Finally, only 50 publications remained and were identified to be related to the use of the Digital Twin for verification and validation. Of these 50 publications, only 33 describe a methodology of how to use a Digital Twin for verification and validation. The remaining 17 publications describe in detail the vision of using the Digital Twin for verification and validation in different application areas in the future.

At this point, we would like to point out once again that this survey does not deal with the verification and validation of the Digital Twin. Instead, the focus of this survey is to show how the Digital Twin can be used for verification and validation. The high amount of false positives in the literature search is due to the terminologically similar but thematically different challenges of verification and validation of Digital Twins, cyber-physical systems, models and simulations.

IV. Analysis of different Approaches

Motivated by the frequent reference that the Digital Twin can also bring great advantages in the field of verification and validation [2–9], a literature search was conducted. This chapter analyses the 33 approaches identified that use the Digital Twin for verification and validation.

The literature review reveals how the Digital Twin is already used to support verification and validation purposes. In order to present the approaches in a structured way, a thematic classification was made. Approaches for verification and validation are categorized according to the degree of abstraction and extensiveness of the input as well as output information. The more meaningful the input information is the more reliable and comprehensive are the results achievable by verification and validation approaches.

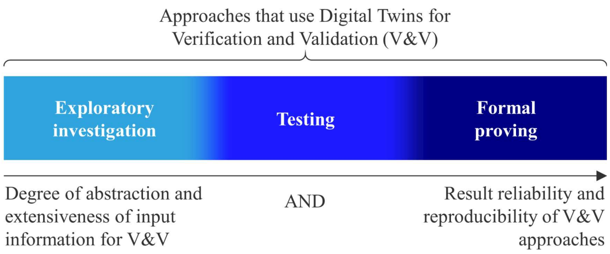

Fig. 1. Categories for the structured presentation of the approaches

TABLE I. Catagorization Results

	Exploratory investigation	Testing	Formal proving
approaches	[23–35]	[36–52]	[53–55]
sum	13	17	3
subsection	IV.A	IV.B	IV.C

As illustrated in Figure 1, there are three categories: Exploratory investigation, testing and formal proving. If there is nearly no input information, exploratory investigations help to develop a first system understanding. With more input information such as requirements and documentation, testing is a good method for verification and validation. For highly critical systems with for example paramount safety and security requirements, results of testing approaches might not be reliable enough. Formal proving with formal verification or model checking methods mathematically proves a certain system behavior. TABLE I. shows the results of this categorization and references to the respective subsection.

A. ***Exploratory investigation*** *with Digital Twin*

This section contains publications in which the Digital Twin is used for verification and validation through exploratory investigation, i.e. approaches that evaluate data of scenarios in order to understand the system behavior in this situation. This may be reached by launching experiments or passively by learning from the system in action.

In the domain of product design and material science, Cerrone et al. as well as DebRoy et al. use the Digital Twin for empirical investigations on produced parts. In [23], a simple material test specimen is simulated. The Digital Twin is used to improve and personalize structural life prediction. To reduce the total number of experiments and decrease costs, DebRoy et al. and Mukherjee et al. use in [24, 25] a Digital Twin of a 3D printer to predict the quality of printed parts. Therefore, many simulations are necessary like for example how well a model is translated to printer commands as well as thermophysical properties of printing materials.

The so called experimentable Digital Twin (EDT) is described in [26–28]. The combination of simulation technology and model-based systems engineering leads to ETDs that allow experiments in the virtual space. Additionally, virtual testbeds (VTB) allow connecting EDTs with real assets. With this approach the task envisioned by West and Blackburn in [29] is to help understand the uncertainties a system is designed for.

In order a support change impact analysis in high-dimensional systems Pairet et al. envision the Digital Twin as integration of different simulation models empowering "exhaustively test [robotic assets] ensuring the coherence and efficiency of the execution plans" [30] in the domain of high-risk environments. In [31] Pereverzev et al. propose an approach for this vision in the moderate-risk environment of CNC machines. They spot the problem that "it is impossible to check the limits of the objective function in the entire array of variable factors combination" [31] and therefore suggest using the Digital Twin for virtual exploring "combined effect of the constantly changing variables, arising while processing a batch of parts" [31]. Macher et al. [32] as well as Fitzgerald et al. [33] propose to exploit the Digital Twin as test oracle using what-if simulations in order to increase the information transparency.

Kühnle and Bayanifar in [34] as well as Veledar et al. in [35] exploit the Digital Twin in the domain of cyber-security for scanning the process data and configuration data for patterns indicating normal or abnormal states. After the patterns have been identified and clustered, they are mapped to normal or abnormal states using heuristics and what-if simulations. The exploratory test data is generated by virtual penetration testing.

Of the 33 approaches examined, 13 use the Digital Twin for exploratory investigation. The Digital Twin is used as a supporting tool for this purpose in the domains of product design and material science, systems engineering, change impact analysis and cyber-security.

B. ***Testing*** *with Digital Twin*

The Digital Twin is not only used to evaluate data of scenarios in order to understand the system behavior but also for extensive testing of properties and functionalities against its specification.

In case of virtual commissioning, the Digital Twin is used as a replacement for missing components. When the physical asset is not available, either since it has not been built yet or because it has been switched off for maintenance or safety reasons, the Digital Twin is used for tests instead. For virtual commissioning, Ayani et al. propose to use reverse-engineering to generate a Digital Twin that can be used afterwards for development as well as validation [36]. Virtual commissioning realizes the verification and validation of a system against models. Engineers carry out tests in a simulated environment. Especially the virtual factory acceptance test (VFAT) proved to be very useful. A similar approach is proposed by Tavares et al. [38] in the domain of robot-based production cells. Orive et al. [39] extend the Digital Twin by fault injection simulations for virtual commissioning scenarios.

The Digital Twin is also used for Software-in-the-Loop (SiL), Hardware-in-the-Loop (HiL) or Model-in-the-Loop (MiL) simulations. Using the Digital Twin as container of the models designed in model-based development, Vathoopan et al. ascribe faults to the affecting factors during downtime of the machines [37]. In contrary, Dufour et al. [40] use a real-time Digital Twin of a ship with Hardware-in-the-Loop capabilities to simulate on-board power systems for virtual tests of subsystem upgrades. This approach considers the Digital Twin to provide a safe virtual test environment. Atlam and Wills [41] contribute to this idea, too. They envision the creation of safe and secure systems by design, because the Digital Twin "capture[s] and visualize[s] a hospital system in order to create a safe environment and test the impact of potential changes on system performances" [41]. Another use case of a virtual safe environment is cyber-security. Becue et al. envision the Digital Twin in the domain of cyber security for supporting "design, testing training and validate of secure by design [Factories of the Future] technologies" [42]. The concept exploits the Digital Twin for simulating and modelling cyber-incidents to test them in advance.

A third field of application of the Digital Twin is to support the assembly of products for quality assessment and virtual assembly. Schleich et al. use in [46] the Digital Twin of produced parts to assist assembly. Before assembly, each part is scanned. The Digital Twins of each part allow to virtual assemble them and virtually determine good fitting part combinations. In [47], Rezaei et al. use scan data to individualize assembly for improved geometrical quality. Based on virtual assembly tests, the torque of the screws used is individually optimized. Sun et al. introduce in [48] the Digital Twin assembly for assembly-commissioning. Here, the Digital Twin is used to support assembly as well as the commissioning of production cells.

Finally, there are approaches to crosscheck simulated process data against real-world process data. Jain et al. [49, 50] contribute to this idea. Starting with the hypotheses of a perfect Digital Twin "that estimates the characteristic outputs precisely in real-time" [50] any (significant) deviation from the simulation to the real world indicates a shortcoming either in the asset (e.g. wear) or in the Digital Twin. Seshadri and Krishnamurthy [51] implement this approach for online-testing structural health parameters (e.g. for plains) based on multi-physics models. Sending waves into the structure under test and measuring the wave signal at different measurement points, the deviation between the modeled wave energy and the recorded one is put into the objective function enabling the location of a crack in the structure under test. Comparing simulated data with preprocessed processed data results in a higher abstraction level. The result is a combination of "discretized state and parameter estimator" [49]. Magargle et al. make use of the Digital Twin in [52] to predict anomalies and therefore improving safety or more generally vehicle health management. The contribution of predictive maintenance to functional safety is highlighted.

Use cases of Digital Twin-based testing of industrial automation systems range from virtual commissioning to virtual modification and from assembly support to model-validation and anomaly diagnosis.

C. ***Formal proving*** *with Digital Twin*

Another aspect of verification and validation is formal proving, which mathematically proves a certain system behavior. Formal proving requires very extensive input information like formal system models as well as formal specifications.

In order to provide these formalized models, Naumchev et al. present in [53] a formal specification framework to facilitate and automate specification extraction and specification formalization for the Digital Twin. This framework supports extracting specifications in natural language from documentation as well as formalizing them. Based on this formalized specifications further verification steps are automated. The resulting Digital Twin early unveils shortcomings of a system by enabling Software-in-the-Loop and Hardware-in-the-Loop simulations. The simulations are designed to perform formal verification and validation.

To formally interconnect dependability models represents a further approach that is presented by Kaul et al. in [54]. For any model, a local dependability estimator is provided. The Digital Twin of the whole system then orchestrates the local estimators into a system-wide estimator modelling the relations of the different models and therefore come to an overall dependability estimation. The approach is integrating formal functional safety models and other dependability models in order to use the prior knowledge to model the link between component stress, types of failure and reliability. With this information, model-specific dependability estimators are built. From the model-specific estimators a system-wide estimation of the dependability is composed mapping together the model-specific estimators.

Lou et al. provide in [55] an idea of using the Digital Twin to perform functional safety and cybersecurity analysis exploiting that most information needed for safety and security analysis is already available. Only some static and dynamic data from the environment has to be added. Their theory is that "a virtual mirror of the real system and its surround environment […][enables the automation of] the predication of potential hazards or security vulnerabilities" [55]. In the first step, they exploit the synchronization of the Digital Twin to inform the safety analyst automatically about changes in the system.

Only three of the 33 analyzed approaches address formal methods. This shows that the major focus is not on formal proving but as shown in Section IV.A on using the Digital Twin for exploratory investigation that is addressed by 13 approaches respectively on using the Digital Twin for testing as presented in Section IV.B that holds 17 publications. Overall, the literature search reveals that the Digital Twin is successfully used for verification and validation purposes. The different methods and various application domains are discussed in the following section.

V. Discussion

After presenting the results of the literature search, this section discusses the three research questions raised in Section 3. Each research question is addressed by a separate subsection.

A. *Essential elements of the Digital Twin for verification and validation purposes*

In order to obtain a statement about still unused potential, with research question one (RQ1), it is investigated which elements of the Digital Twin are used by the 33 analyzed approaches. As presented in Section II.B, a full featured Intelligent Digital Twin comprises the following five elements:

- Provisioning of models and engineering artefacts
- Provisioning of simulations, executable models
- Processing and storage of operation data
- Synchronization mechanisms
- Communication to other Digital Twins

The results of what elements of the Digital Twin the 33 analyzed approaches use for verification and validation purposes are shown in TABLE II.

The investigation of the elements showed: The accessibility of the models is the striking benefit of the Digital Twin for verification and validation. All approaches make use of models that are provided by Digital Twins. Furthermore, 19 of the 33 approaches make use of simulations that are made available by a Digital Twin. A central interface providing both operational data and data analysis has proven useful for engineering and monitoring purposes. In total 15 approaches make use of this Digital Twin feature.

It is not surprising that models, simulations and operational data are used for verification and validation purposes. However, it is remarkable that the additional capabilities of the Digital Twin are not exploited. The other elements of Digital Twins like synchronization mechanism and communication to other Digital Twins are not used by the analyzed approaches.

TABLE II. Digital Twin elements used for Verification and Validation purposes

	Usage of models provided by Digital Twin	**Usage of simulations provided by Digital Twin**	**Usage of operation data provided by Digital Twin**
Approaches	All	[23, 24, 26–28, 30, 36–43, 47, 48, 50, 52, 53]	[25, 28, 31–36, 40, 41, 44, 49–51, 55]
sum	33	19	15

No usage of synchronization mechanisms is surprising since the synchronization of the models during the complete life cycle is the main distinction of the Digital Twin compared to model-based engineering or other usages of models as stated in [2]. Because of that, strictly speaking, no approach really requires the Digital Twin, as no approach utilizes the synchronization of the models. Of course, every model-based approach benefits from up-to-date models, but none of the analyzed 33 approaches uses and demonstrates the benefits of updated models.

The synchronization of models could bring huge benefits for automated, dynamic verification and validation during operation. Such dynamism is important for systems changed during operation, especially in the fields of flexible manufacturing as mentioned in [56] and in the field of autonomous systems. As stated in [57], intelligent autonomous systems self-adapt during operation and have therefore to be validated continuously during operation. Such dynamic verification and validation of changing autonomous systems requires consistent, up-to-date models, which can be achieved by the synchronization mechanisms of the Digital Twin.

It is also remarkable, that only few approaches utilize both, simulation and operation data. The combination of both, which according to [2] can be easily achieved by the Digital Twin, also harbors potential benefits, as the simulations can be substantiated by operation data, which can lead to more accurate results, as historic data is considered.

Additionally no approach utilizes the communication between Digital Twins. This communication can be used to get data from other Digital Twins and therefore data describing the environment of the physical asset to be validated. This can be achieved for example by co-simulation, which adds to the verification and validation results the responses and reactions of other systems to actions of the asset-under-inspection. In particular, this is helpful for the automation of verification and validation processes that require the interaction of several systems.

Results: For all three of those findings, no usage of synchronization, rare combination of simulation and operation data and no usage of communication between Digital Twins, more research has to be done in the future. This leads to a variety of open research questions. The objective is to use the full potential of the Digital Twin for verification and validation purposes by using all elements of it. The analyzed approaches mainly focus on the simulation aspect. The practical understanding of what constitutes a Digital Twin often refers only to the simulations provided by it.

Nevertheless, if a Digital Twin is to be created for verification and validation or an existing Digital Twin is to be used for this purpose, TABLE II. can be used to reconcile the requirements of the individual approaches.

B. Clustering of methodologies

As discussed in the previous section, many approaches focus on simulations. Due to this, methodological similarities can be observed. To help with the harmonization of terminology and to answer research question two (RQ2), the authors identified three major methodological clusters and propose to name them as follows. Approaches are assigned to the same cluster if they share a similar underlying methodical core or application goal. The 33 approaches presented in Section IV are assigned to one of the following three clusters:

- What-if analysis
- Cross-validation
- Evidence advice

TABLE III. holds the results of the methodological clustering. Out of 33 approaches, 21 pursue the idea to use the Digital Twin to obtain information about system or respectively asset behavior. For this purpose, assumptions are verified and validated in whole or in part in a virtual model and simulation environment. These approaches are assigned to the methodological cluster **what-if analysis**. This cluster includes approaches from the areas of big data driven analysis, what-if and prognosis simulation and Hardware- (HiL), Software (SiL) and Model-in-the-Loop (MiL) simulations. In what-if and prognosis simulations, various options for action are evaluated with the aim of answering the question "what happens if a specific option is chosen? " In HiL, SiL and MiL simulations, non-existent assets or environments are simulated and questions such as "what if some missing parts would work as intended" are examined.

From 33, only five approaches focus on using the Digital Twin in combination with model validation techniques, especially cross-validation of models. These approaches were assigned to the methodological cluster **cross-validation**. This cluster comprises approaches that use analytical methods to detect differences between models and the behavior of real systems. This also includes approaches for anomaly detection and approaches where a Digital Twin is used to monitor systems and diagnose faults.

TABLE III. METHODOLOGICAL CLUSTERS

	What-if analysis	Cross-validation	Evidence advice
Approaches	[24, 26–28, 30–33, 35–40, 42–44, 46–49]	[23, 34, 50–52]	[25, 29, 41, 45, 53–55]
sum	21	5	7

TABLE IV. APPLICATION DOMAINS OF DIGITAL TWINS USED FOR VERIFICATION AND VALIDATION PURPOSES

Applications domains	Publications on engineering	Publications on operation
Aviation and aerospace	[27, 29]	[43, 51]
Manufacturing systems	[28, 36, 38, 39, 45, 53]	[31, 37, 44, 54]
Product design and assembly	[23–25, 32]	[46–48]
Robotics	[26, 33]	[30]
Power Systems	[40]	[49, 50]
Safety and Security	[41, 42, 55]	[34, 35, 52]

The third cluster **evidence advice** includes seven approaches, where the Digital Twin is used as a sort of intelligent system to measure test coverage or respectively to find gaps in test coverage. Approaches use the Digital Twin to increase the accessibility of test results and to automatically analyze the data generated during testing.

Results: The benefit of this search for methodical clusters is to show, that until now there are three main ideas of how to use a Digital Twin for verification and validation. With 21 out of 33, the majority of the approaches found use the Digital Twin to simulate or predict system behavior. The Digital Twin makes it possible to break new ground here. As discussed in the previous section, the use of synchronization mechanisms is underdeveloped. But with what-if analysis that profit from automatically updated models and hence automatically renew their simulation results, many verification and validation use cases can be automated and dynamically repeated.

The Digital Twin is also useful to compare modelled and real behavior by means of cross-validation or to act as an evidence storage and test oracle. These are very interesting ways to exploit the full potential of Digital Twins. Further research questions therefore arise regarding the expansion and combination of existing methods. As shown in the previous section, there is still unused potential so new methods may be added in the future, too.

C. Application domains of the Digital Twin

To better coordinate research and to answer research question 3 (RQ3), it is also important to understand the variety of application domains. In order to get an overview on where Digital Twins are used so far for verification and validation purposes, all 33 approaches are analyzed with regard to this. As shown in TABLE IV. , in total six application domains were identified.

Out of 33, ten publications address the manufacturing systems domain. In general, there is a lot of Digital Twin focused research in this area, which will contribute to a rapidly increasing dissemination of Digital Twins here. Like symbiosis, this will enable many verification and validation applications that use the Digital Twin in the area of manufacturing systems. In the future, even larger parts of verification and validation processes than today can be done virtually, as Digital Twins increase abilities in the virtual space and model world. This will further increase sophistication in virtual commissioning and enhance engineering efficiency. An also frequently addressed application domain of the Digital Twin used for verification and validation purposes is the often very general problem domain of safety and security. Further application domains are aviation and aerospace, product design and assembly, robotics as well as power systems. It is possible to further distinguish between publications that use a Digital Twin to support verification and validation purposes of the engineering or the operation phase as illustrated in TABLE IV. This shows that the Digital Twin is able to support verification and validation purposes throughout the entire asset life cycle.

Results: The examination of application domains shows, that the Digital Twins is already considered as a viable solution in six application domains. TABLE IV. can be used to identify approaches from other application areas but similar problems. Further research could focus on the adoption of existing approaches in other application domains.

VI. Conclusion and Outlook

As mentioned in [2–9], the Digital Twin is envisioned to have great potential in the field of verification and validation. This paper presents an overview of how the Digital Twin is used for verification and validation purposes so far. A total of 33 publications were examined and discussed based on three research questions. Goal of this paper is to coordinate research and guide practitioners to suitable approaches. The Digital Twin supports exploratory investigation as well as testing. There are also few approaches in the field of formal methods.

All of the 33 approaches identified make only very limited use of the possibilities of the Digital Twin as discussed in Section V.A. Thus, the Digital Twin is mainly used for the provision of specific models and simulations, partly also for operating data. However, the main purpose of the Digital Twin according to [2] lies in the provision of up-to-date models throughout the entire asset life cycle. This requires synchronization mechanisms, which are not considered by the analyzed approaches. In section V.B, the methodological clustering of the 33 approaches revealed three main ideas of how to use the Digital Twin for verification and validation. With what-if analyses, predictions about the behavior of the physical twin are obtained from the virtual space through simulations. Cross-validation checks actual against modelled behavior. Furthermore, the Digital Twin is used as an evidence storage to show which parts are already tested. In the 33 approaches analyzed, the Digital Twin is used in six different application domains as shown in Section V.C. Much research is being done especially in the field of manufacturing systems.

Digital Twin is a fast emerging topic and as stated before there is unused potential for verification and validation purposes. The Digital Twin is well suited to increase the efficiency of verification and validation by facilitating the use of models and simulations. However, the Digital Twin can do even more. The fact that the models are synchronized with the real asset over the entire life cycle and thus always kept up to date creates new possibilities and raises new research questions. Dynamic verification and validation of assets at any time become possible. Virtual findings can be crosschecked with real operational data. Discoveries during the operational phase can be used to improve the models. With better models, more reliable conclusions and predictions can be made. The result would be a closed quality improvement loop, which can also be automated and thus especially contribute to the field of reliable autonomous systems. The design and evaluation of such a life cycle overarching approach poses a great challenge.

More is also possible in the area of the models considered so far. Besides simulation models, the Digital Twin can contain all models from the field of model-based engineering. Having the Digital Twin established over the whole lifecycle the concept of model-driven engineering can be supported. A great strength of the Digital Twin is the linking of models, thus, model transformation that is the main underlying method of model-driven engineering can be eased. The linking of models as well gives great potential in the area of reliability and safety assessment during runtime. For example, models of failure mode and effects analysis (FMEA) and fault tree analysis (FTA) can also be kept available via the Digital Twin. The aim would be to speed up safety assessments after changes. Models for model-based testing, subjective logic or model checking can also offer great benefits. Combining new methods with Digital Twin technology would expand the application areas for Digital Twins.

In summary, the Digital Twin acts as an intelligent interface between the model universe and the real asset. To date, the full potential of the Digital Twin has not yet been exploited for verification and validation purposes. In the future, an automated closed quality improvement loop with feedback on development is conceivable.

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