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RESEARCH ARTICLE

Digital Twins in Manufacturing: A Systematic Literature Review With Retrieval-Augmented Generation

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ABSTRACT This paper presents a systematic literature review on the use of digital twins in manufacturing, with the goal of developing a comprehensive taxonomy that synthesizes existing categorizations. Given the increasing complexity and volume of literature in this domain, conventional review methods are becoming insufficient. To address this challenge, the study applies a novel approach named retrieval augmented generation. This is a technique that combines large language models with real-time information retrieval, enabling the automated identification and summarization of typologies across a broad corpus of publications. A total of 1,354 publications were initially screened, leading to 144 distinct categorizations relevant to digital twins in industrial contexts. The resulting taxonomy classifies digital twins along multiple dimensions, including life cycle stages, physical domain and hierarchy levels, model characteristics, digital thread connectivity and deployment strategies. This work provides both researchers and practitioners with a structured approach to understanding and implementing digital twins in manufacturing environments, as well as a guideline to completely describe a specific implementation. The taxonomy serves as a foundation for future research and as a practical tool for industrial applications, since it defines design decisions, which have to be made.

INDEX TERMS Digital twins, taxonomy, systematic literature review, manufacturing systems, retrieval-augmented generation.

I. INTRODUCTION

The digital twin concept underlies a growing interest of researchers and practitioners. The global digital twin market is expected to rise from 5.6 Billion USD in 2019 to 195.4 billion USD in 2030 [1]. A study from 2022 shows, that the companies, which are using digital twins (DTs), could improve their operational efficiency on average by 15 % [2]. Furthermore, 68 % of the asked organizations see a simulation as a service from the DT, justifying its use [2]. Biesinger and Weyrich name a few more benefits of DTs in production, for example increased productivity, reduced complexity, time savings and lower costs [3]. This interest leads to a considerable field of publications: In January 2025, a search for the term "Digital Twin" in Google Scholar leads to 1,420,000 hits overall and 18,200 hits since 2024 alone. It is therefore challenging to gain an overview of the research landscape by a classical literature review.

This is where retrieval augmented generation (RAG) comes into play. RAG enhances the capabilities of large language models (LLMs) by incorporating external, dynamically retrieved information into their generative processes. This approach not only improves the accuracy of the response and reduces hallucinations [4], but also allows the model to operate on a significantly broader information base. By retrieving and injecting relevant textual chunks from a large corpus into the prompt, RAG enables automatic coverage of a wider range of scholarly papers than is typically

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feasible with conventional literature review methods. As a result, RAG is particularly suited to automate key steps in systematic literature reviews (SLRs), including literature search, screening, data extraction, and synthesis, thus enhancing the efficiency, scalability, and comprehensiveness of academic research.

The aim of this study is to give an overview of the field of digital twins specifically in manufacturing by creating a taxonomy, showing different types of digital twins, and naming possible applications and features.

The contributions of this study are twofold. First, we demonstrate how retrieval augmented generation (RAG), which combines large language models with real-time information retrieval, can be effectively applied to conduct systematic literature reviews in the context of digital twins in manufacturing. Second, based on the insights from this analysis, we develop a comprehensive taxonomy of digital twins that supports their conceptual understanding, practical implementation, and complete and consistent description across industrial contexts.

This is done by searching for categorizations of digital twins in manufacturing in existing literature, utilizing RAG. In section II related work on taxonomies for digital twins is discussed. In section III, an overview of utilizing RAG for literature searches and a method for the creation of taxonomies is given. The conducted literature search for characteristics, which can be used to distinguish different types of DTs is shown in detail in section IV, as well as the results. These characteristics are used to create a taxonomy, following the method proposed by Nickerson et al. [5]. This is done in section VI. In section VII, the methodology and the results are critically discussed and in section VIII the paper ends with a conclusion.

II. RELATED WORK

Several categorizations of DTs have been proposed. Kritzinger et al. [6], define three subtypes of digital twins, according to their connection between the physical and the digital object. If the connection is completely manual, the digital twin is categorized as a digital model (DM, Figure 2). If the digital object is updated through an automatic data pipeline, it is categorized as a digital shadow (DS, fig. 3). If both data connections, from the physical model to the digital model and vice versa are automatized, it is categorized as a digital twin (DT, Figure 4). This leads to an endless recursion, since the DT is a subtype of itself. This is also criticized by other authors, for example, Barbie and Hasselbring, which state that a customer might expect to purchase a DT, as advertised by vendors, only to receive a DM instead [7]. Another way to categorize DTs is the reference architecture model for industry 4.0 (RAMI4.0) [8], which is shown in Figure 1. In combination with the asset administration shell [9], this model describes the integration of DTs into the companies IT-infrastructure [10]. DTs itself are differentiated in two dimensions: The hierarchy level and the life cycle. The hierarchy level is derived from the

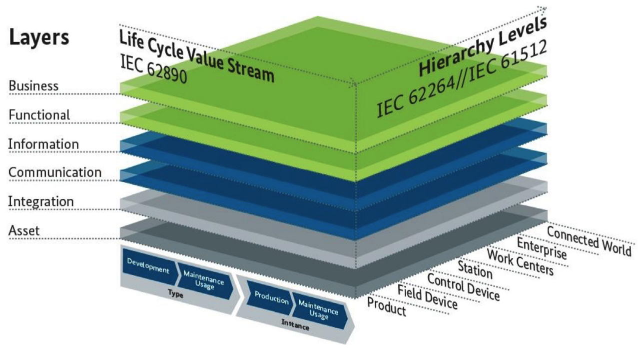

FIGURE 1. Reference architecture model for industry 4.0 [8].

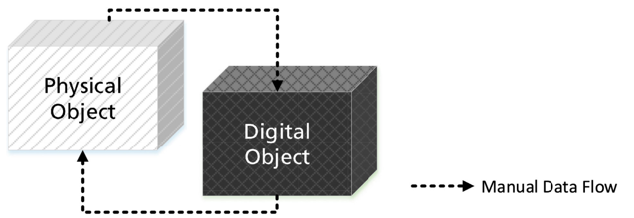

FIGURE 2. Digital model according to Kritzinger et al. [6].

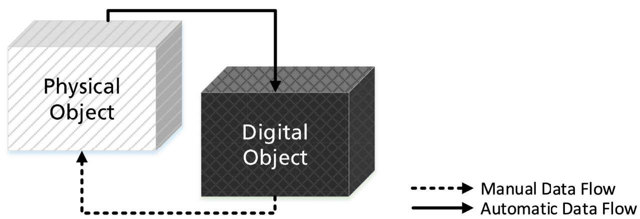

FIGURE 3. Digital shadow according to Kritzinger et al. [6].

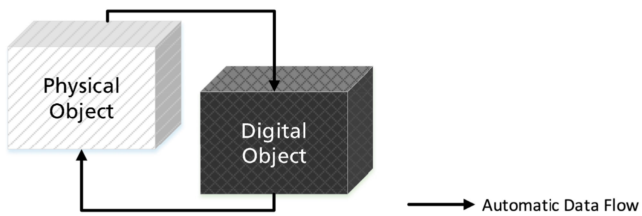

FIGURE 4. Digital twin according to Kritzinger et al. [6].

automatization pyramid, but extended by the product at the lower end and the connected world at the upper end. The life cycle is divided into two categories: The type of the product and the instance, which are further divided into a creation stage and a usage stage. A limitation of this model is that the category product is not actually on the same dimension as the other categories of the hierarchy level. A complex product can also consist of different control and field devices, which are not described by the model.

In a recent publication, Barbie and Hasselbring [7] have formalized the different concepts in the digital twin context:

- **Physical Twin:** A physical twin is a real-world physical system-of-systems or product. It comprises sensing or actuation capabilities driven by embedded software.

- **Digital Model:** A digital model describes an object, a process, or a complex aggregation. The description is either a mathematical or a computer-aided design.
- **Digital Template:** A digital template serves as a framework that can be tailored or populated with specific information to generate the physical twin. It encompasses the software operating the physical twin, its digital model, and all essential information needed to construct and sustain the physical twin. These contain, for example, blueprints, bills of materials, technical manuals, and similar documentation.
- **Digital Thread:** The digital thread refers to the communication framework that allows for a connected data flow and integrated view of the physical twin's data and operations throughout its life-cycle.
- **Digital Shadow:** A digital shadow is the sum of all the data that is gathered by an embedded system from sensing, processing, or actuating. The connection from a physical twin to its digital shadow is automated. Changes on the physical twin are reflected to the digital shadow automatically. However, the digital shadow does not change the state of the physical twin.
- **Digital Twin** A digital twin is a digital model of a real entity, the physical twin. It is both a digital shadow reflecting the status/operation of its physical twin, and a digital thread, recording the evolution of the physical twin over time. The digital twin is connected to the physical twin over the entire life cycle for automated bidirectional data exchange. Changes made to the digital twin lead to adapted behaviour of the physical twin and vice versa.
- **Digital Twin Prototype:** A digital twin prototype (DTP)is the software prototype of a physical twin. The configurations are equal, yet the connected sensors/actuators are emulated. To simulate the behaviour of the physical twin, the emulators use existing recordings of sensors and actuators. For continuous integration testing, the DTP can be connected to its corresponding digital twin, without the availability of the physical twin.

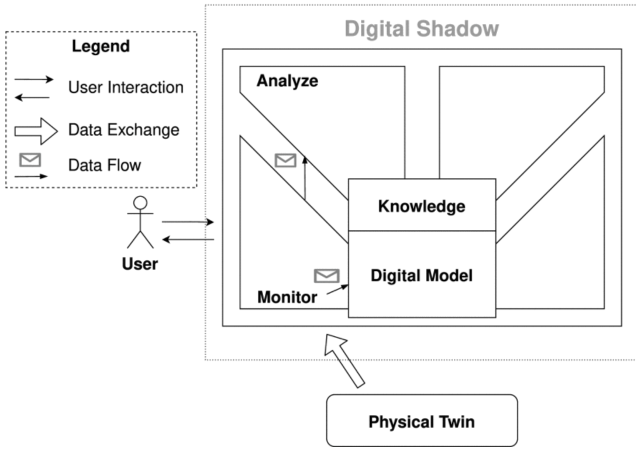

FIGURE 5. Digital shadow according to Barbie and Hasselbring [7].

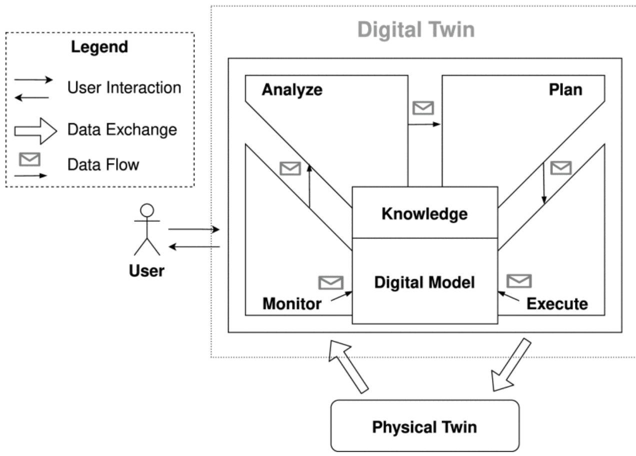

FIGURE 6. Digital twin according to Barbie and Hasselbring [7].

The main difference to the definition of Kritzinger et al. is, that they do not distinguish between the digital model (DM) and the DT / DS, but they see the digital model as a part of the DS / DT (see Figure 5, Figure 6). Thus, a DT and a DS interact with the physical twin and the DM. The difference between the DT and DS is, that the DT has features that allow for controlling the physical twin. But this categorization does not consider the different hierarchy levels, in which DTs can be applied, as stated in the RAMI 4.0 model.

Other categorizations are created based on literature.

Brennan and Lesage categorize digital twins, but use just one dimension, namely the modelling approach, with the dimensions physics-based model and data-driven model [11]. Likewise, did Vogel-Heuser et al., but using the engineering domain as single differentiation dimension [12]. Berti and Serena use the dimensions focussed area (manual assembly, material handling, HRC assembly and other) and human factor (Ergonomic risk assessment, worker's safety, mental/physical workload) [13]. Liu et al. categorized DT applications according to its application stage and specific application [14].

Pystina et al. used more dimensions, namely physical twin, approach, features, deployment strategy, structure and DT Intelligence, but did not specify specific categories for these dimensions [15].

Cimino et al. categorized implementations of DTs, based on 52 articles, found during a literature search [16]. The dimensions contain system features, implementation features and DT-Services. Considering the huge amount of DT-literature, 52 implementations are a small sample size. Moreover, some dimensions like the simulation software type is not applicable for some implementations.

Liu et al. conducted a literature review, to first combine different reference models [17]. Furthermore, they categorized literature of information modelling, physical entity virtualization and knowledge modelling and other use cases, but without using consistent categories.

More comprehensive, Webb et al. [18], have analysed 60 articles to create the taxonomy of DT-enabled

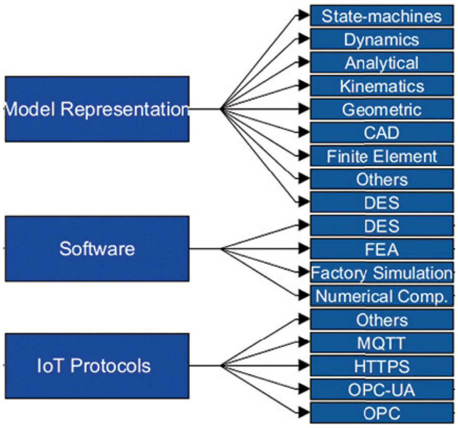

FIGURE 7. Excerpt from a taxonomy for DT-enabled assembly automation [18].

assembly automation. The methodology was to search for DT-implementation scenarios and to categorize them. Due to the large number of different studies, not all categories of the various dimensions are clearly defined. For example, the dimension ''Model Representation'' includes the category ''Others''. Furthermore, category discrete event simulation (DES) is named twice in the dimension model representation and software, as shown in Figure 7.

Most existing categorizations limit themselves to a few dimensions [6], [11], [12], [13], [14]. This is often because their goal is not to develop a comprehensive taxonomy, but rather to classify the literature according to the specific research interests of the authors. Conceptual frameworks such as RAMI 4.0 similarly do not reflect the dynamically evolving research field, since their primary purpose is to provide a reference architecture for structuring technical developments. Instead of offering an overview of digital twin research in the production context, RAMI 4.0 is primarily directed at industry to support the development of interface standards. Approaches such as that of Webb et al., which categorize publications on implemented digital twins to derive a taxonomy, face limitations due to the sheer volume of research. Their study, for example, is based on 60 implementations [18], which represents only a small fraction of the broad and rapidly growing field. In contrast, our approach builds on existing categorizations by other researchers like [6], [11], [12], [13], and [14], thereby integrating their domain-specific expertise into the taxonomy and capturing a broader spectrum of the overall research landscape. In doing so, our work extends beyond individual categorizations by synthesizing them into a comprehensive taxonomy of digital twins that advances their conceptual understanding, supports practical implementation, and ensures a consistent description across industrial contexts.

III. METHODOLOGY

We will use RAG, to find categorizations of other researchers, in the field of digital twins in manufacturing. We will use these to create a taxonomy of digital twins, using the methodology of Nickerson et al. [5]. Both methods will be described in the following subsections.

A. RETRIEVAL-AUGMENTED GENERATION FOR LITERATURE REVIEWS

The exponential increase in scientific publications — particularly in rapidly evolving domains such as DTs — has rendered traditional literature review methods increasingly inefficient and difficult to scale. Researchers now face significant challenges in tracking ongoing developments, identifying relevant studies, and synthesizing insights across a growing body of knowledge. Retrieval-augmented generation (RAG) has emerged as a promising solution to this problem, offering an approach that augments large language models (LLMs) with real-time access to external knowledge sources. Unlike conventional LLMs that rely solely on pre-trained data - which may quickly become outdated - RAG dynamically retrieves up-to-date data from structured and unstructured sources. This capability proves especially valuable for literature reviews in rapidly evolving domains, where emerging trends, methodologies, and technological innovations require continuous monitoring [4].

A typical RAG architecture consists of two core components: the retriever and the generator [19]. In the first stage, the retriever identifies and extracts semantically relevant text segments - commonly referred to as chunks - from documents ingested in real-time in response to the query. All chunks are stored and organized within a vector database such as Chroma [20], using a configurable chunking strategy. This strategy involves syntactic or semantic splitting of all real-time documents. This incorporates an overlap between adjacent chunks to preserve contextual continuity and maintain coherence across boundaries. Each text chunk is converted into a high-dimensional vector embedding using embedding models that capture its semantic meaning. These embeddings are then indexed in the vector database, allowing efficient retrieval based on similarity.

When a user submits a query, a similarity search retrieves the most relevant chunks, forming the evidence base for the second stage of the generator component [21]. The generator uses the retrieved chunks to refine and enhance the original query [22] and formulates the answer based on a typically pre-trained LLM. A detailed description of the RAG-Setup is stated in Appendix A.

By integrating dynamic retrieval with generative synthesis, RAG models deliver outputs with improved accuracy, relevance, and contextual depth compared to stand alone LLMs. Their capacity to automatically process large volumes of domain-specific literature makes them ideal for supporting or fully automating tasks associated with systematic literature Reviews (SLRs), including study selection, information extraction, and thematic synthesis [4].

In summary, RAG-enhanced LLMs offer a transformative approach for managing and synthesizing scientific knowledge, ensuring literature reviews remain comprehensive and current in rapidly advancing domains.

B. METHOD FOR CREATING A TAXONOMY

The aim of this paper is to create a taxonomy for digital twins in manufacturing. Nickerson et al. have proposed an iterative method to develop taxonomies in information systems [5], which is shown in the following:

1) Determine a meta-characteristic to define the subject
2) Determine ending conditions
3) Chose one approach:
   - Conceptual-to-empirical
     a) Conceptualize characteristics and dimension of objects
     b) Examine objects for these characteristics and dimensions
     c) create (revise) taxonomy
   - Empirical-to-conceptual
     a) Identify subset of objects
     b) Identify common characteristics and group objects
     c) Group characteristics into dimensions to create (revise) taxonomy
4) Ending conditions met?
   - No: Go back to 3)
   - Yes: End

First, a meta-characteristic has to be determined, since it serves as the basis for the choice of characteristics in the taxonomy [5]. The aim of this study is to give an overview of the field of DTs specifically in manufacturing and to support practitioners and researchers by defining a specific implementation of DTs. We therefore determine the meta-characteristic to be the functional design of digital twin implementations.

The next step is to determine ending conditions. We will use the subjective ending conditions from Nickerson et al. (the taxonomy should be concise, robust, comprehensive, extendable and explanatory). Regarding the objective ending conditions, we will use that the taxonomy was not changed any more in the last iteration, that at least one object should be classified under every characteristic of every dimension. Furthermore, there should not be a dimension- or characteristic duplication. We will neither use that there should not be a cell duplication nor that every object has to be examined. This is because there are too many implementations of DTs to examine them all. Moreover, there might be implementations which are identical according to our taxonomy, and we don't see this as an issue because our aim is to categorize DT implementations, not finding individual ones.

According to Nickerson et al., the empirical-to-conceptual approach is advised, if little data of subjects is available but significant knowledge of the researchers over the field of interest [5]. On the other hand, if the researcher has little understanding of the domain, but significant data about the objects are available, the conceptual-to-empirical method is advised. We will use RAG to identify different categorizations of Digital Twins in manufacturing, which were created by other researchers. In this way, we will leverage their knowledge to create a first conceptual taxonomy. Then we will use the method of Nickerson et al., to further refine this taxonomy.

IV. RAG BASED LITERATURE SEARCH

The literature is analyzed, whether a differentiation between different subtypes of digital twins is made. Since this differentiation might not be mentioned in the title, abstract, or keywords, a more general search term is used to identify general literature regarding DTs in a manufacturing context. The search is performed on the 20th of October 2024 in SCOPUS, using the term *TITLE("Digital Twin" AND (production OR making OR producing OR manufacture OR manufacturing OR fabrication))*. The aim is to find all journal- and conference paper, which deal with DTs in a manufacturing environment. No other constraints were made, so the search leads to 1.354 results. A flow diagram of the literature search according to PRISMA [23] is shown in fig. 8. From the initial results, the following articles were sorted out, leading to 1026 remaining articles:

- Articles, without accessible full text.
- Articles, which are not written in English
- Articles, which are not published peer viewed in a scientific journal or a conference proceeding

As mentioned above, if a differentiation between subtypes of DTs is made in a paper, it is not always mentioned in the title, abstract, or keywords. Therefore, the whole text has to be analyzed. In this study, this is done by using RAG.

First, the full text, which is supplied as a.pdf, is converted into a string by a PDF reader in python. Then, the text is divided into chunks, which are stored in a vector database. In the next step, a similarity search is performed to get the chunks of the paper, which fit best to a specific context. Then, the LLM is supplied with the chunks and is asked to answer a specific question, based on the supplied information. Two questions are asked:

1) Is a categorization or typology of digital twins or similar concept created in this paper?
2) Summarize the categorization or typology of digital twins or a or similar concept, used in this paper.

The first question is designed as a yes or no question. Therefore, every paper where the RAG agent cannot detect a differentiation, can be sorted out directly. If a categorization is found, it is summarized. To enhance reproducibility, the AI analysis is done multiple times, with different chunk sizes and numbers of chunks, which are passed to the LLM. If a single configuration has found a categorization, the paper is considered in the first manual analysis. The RAG agent found 468 categorizations. The following review process was done by one researcher.

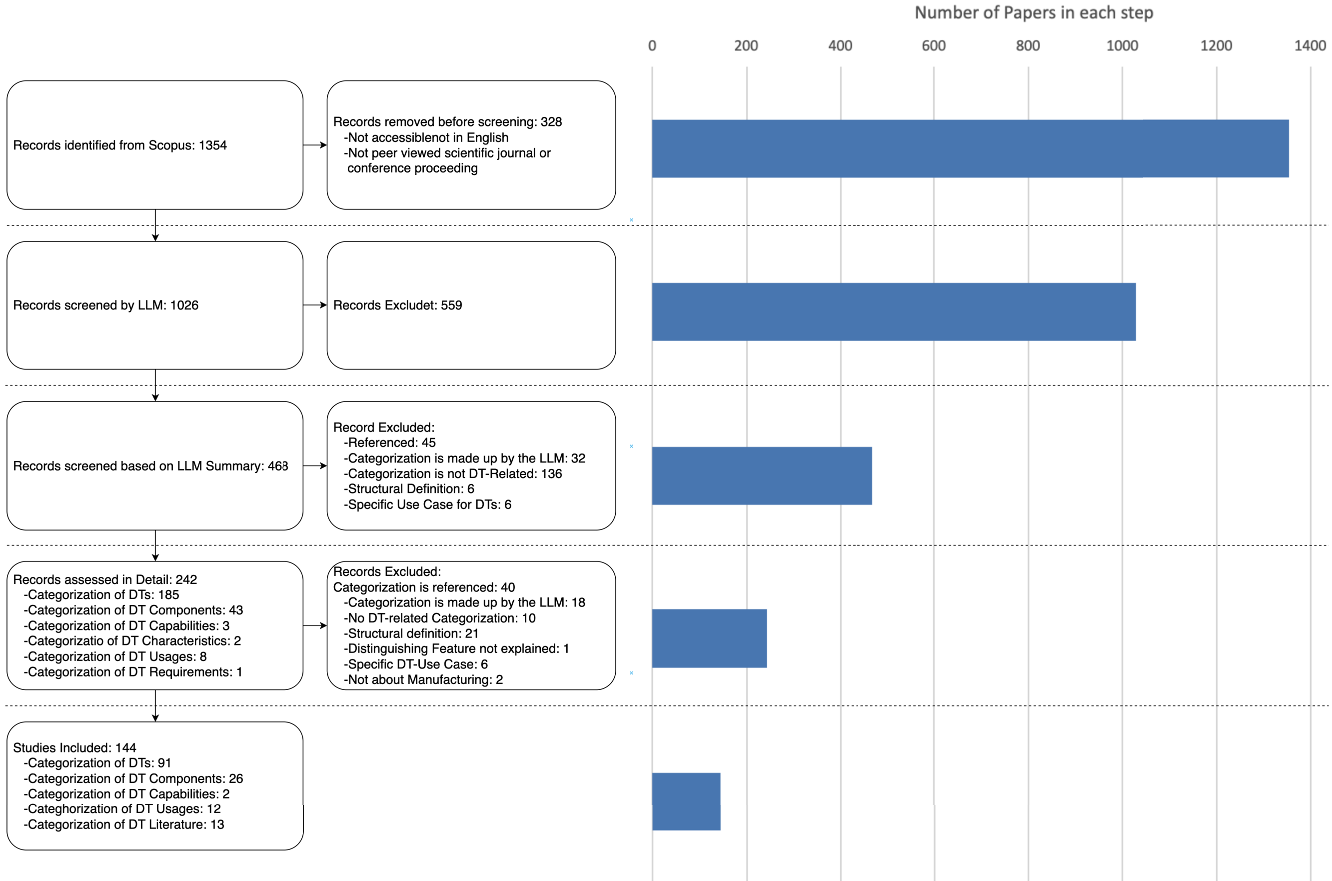

FIGURE 8. Flow diagram of the literature search according to PRISMA [23].

The summary, created by the LLM, is checked whether the paper is considered for further analysis or not. The exclude criteria shown in fig. 8 are used. After this step, 242 articles are left. In the next step, the full texts of the articles are checked, if there is a categorization of DTs. This results in 144 categorizations, which are used in this paper. An overview of all reviewed literature, as well as the RAG summaries and the used include- and exclude criteria, is available in [24].

V. RESULTS

Based on the findings of the literature review, a preliminary dimension and set of categories are assigned to each categorization. Subsequently, semantically equivalent dimensions are consolidated, and overarching categories are derived. The following section outlines this process in detail.

A. LIFE CYCLE

Several authors distinguish between different phases of the product life cycle, in which the digital twin is applied. Based on the definitions of Barbie and Hasselbring, the digital template is used in the design phase of the twin. In the prototype phase, a digital twin prototype is used and the DT or DS can be used if there is a physical twin. The different life cycle phases used in the literature are stated in Table 1. It can be seen that the categorization of Rasor et al. [25] describes all other categorizations on a higher granularity with production, integration, operation, and end of life. We will therefore use this categorization for the life cycle of DTs/DSs.

B. DOMAIN AND HIERARCHY LEVEL

When looking at the RAMI 4.0 model, the dimension of the hierarchy level is an extension of the automatization pyramid, since on the lower end the product was added. Actually, this is inconsistent: While a manufacturing station consists of several control devices, which consists of several field devices, the field device does not consist of several products. On the other hand, a complex product, for example a car or a manufacturing station can also consist of several control devices, which consist of several field devices. Therefore, we propose to differentiate the physical twin first between different domains and on a second level between different hierarchy levels. We identified the following categories for the domain, in which the DT is applied: Product, production, human, resource, process, environment. Table 2 gives a description for each domain as well as references, where the

TABLE 1. Life cycle phases used in the digital twin concept.

Author	Digital Template	Digital Twin Prototype	Digital Twin / Digital Shadow			
Rasor et al. [25]	Design	Development	Production	Integration	Operation	End of Life
Lechler et al. [26]	Type		Instance			
Moller et al. [27]	-	Prototype	Instance			
Liang et al. [28]	Design and Simulation	Development and Deployment			Operation and Management	
Cheng et al. [29]	Design	-	Manufacturing	-	Service	Recycling
Krückenmeier and Anderl [30]	as-designed	-	as-built / as-post-processed	as-qualified	-	-
Yang et al. [31]	Design	-	-	-	Operation / Maintenance	-
Liu et al. [14]	Design	-	Construction	-	Operation and Management	-
Grieves [32]	-	Digital Twin Prototype	Digital Twin Instance			
Timperi et al. [33]	Product in Portfolio	-	-	Delivered Instance	-	-

TABLE 2. Domains of digital twins.

Domain	Description	Usage
Product	Describes the Product. Either the digital template, the digital twin prototype or the physical product, which is produced, depending on its life cycle. It can also be categorized by its hierarchy level.	[15], [39]–[57]
Production	Refers to the physical production equipment, like plants, machines, tools etc. It can be further divided by its hierarchy level.	[12], [54]–[56]
Human	Refers to the human, which is interacting with the physical twin.	[40]
Resource	Refers to the resources, which are consumed during the production process, for example energy, raw materials or parts.	[41], [43], [45], [46], [49], [52]
Process	Refers to processes, which takes part in the production of products. Besides the production process, there are for example maintenance or logistics processes.	[15], [39], [41]
Environment	Refers to the environment, which is affecting the production. This can be a physical building or the climate.	[39], [51], [57], [58]

exact domain is used. Several authors use similar domains but with other names [34], [35], [36], [37], [38].

Categorizations regarding the hierarchy level are stated in Table 3. The heading categories are based on the RAMI 4.0 model but without the category product because we see this as a domain category. All stated categories refer to an equivalent of the RAMI 4.0 categorization, but not every categorization has equivalents to all RAMI 4.0 categories. We therefore propose to use the RAMI 4.0 categorization without the product category to describe the hierarchy level of a DT. Field devices in this context are single sensors or actuators. Control devices might be PLC devices, which control several field devices. A station consists of several control devices, which work together in a complex machine or, for example, a car. Work centres consist of several independent machines. Enterprises are self-explanatory, and the category connected world considers digital twins, which use data from multiple enterprises. Not shown in Table 3 are two categorizations. Gutman et al. differentiate between macro- and micro level [59], which is too unspecific. Kos et al. distinguish DT instances, DT aggregated and DT system [60], which is a hierarchy specific to DT systems and not suitable for product or production.

C. MODEL

To categorize the digital model, the collected categorizations regarding the model are reviewed. As shown in Table 4, six authors differentiate the model according to their visibility. Furthermore, Böttjer et al. [73] differentiates physical models between first principles, data driven and hybrid. We see physics based, model driven and simulation based as synonym to white box, hybrid, and combination as synonym to gray box and data driven as synonym to black box. Therefore, we categorize every model as either white-, gray- or black box model. Moreover, we identified the following types of white box models, which are not specific to a use case:

- Geometry [18], [73], [79], [80], [81], [82]
- Equation [80]
- Behavioral Model [73], [79], [82]
- Rule Model [73], [82]

We propose to use this second layer of differentiation for white- and grey box models. Further differentiation between black box models could not be derived from the literature.

Another way to distinguish different models, is their fidelity. Kober et al. name the three dimensions tolerance, frequency, and latency [83]. Lechler et al. distinguish different synchronization speeds between PT and DM, namely asynchronous, near real-time and real time [26]. Those can be considered the latency according to Kober et al. Wallner et al. also categorizes into the three different rates of changes low frequency, medium frequency and high frequency [84], which can be interpreted as the frequency, according to

TABLE 3. Hierarchy levels of digital twins.

<table>
<tr><th>Author</th><th>Field Device</th><th>Control Device</th><th>Station</th><th>Work Centres</th><th>Enterprise</th><th>Connected World</th></tr>
<tr><td>Sulak et al. [61]</td><td colspan="2">Transition</td><td>Machine</td><td>Line</td><td>-</td><td>-</td></tr>
<tr><td>Luo and Ball [62]</td><td>-</td><td>-</td><td>Block</td><td>Module</td><td>Member</td><td>System</td></tr>
<tr><td>Rasor et al. [25]</td><td>-</td><td colspan="3">Subsystem</td><td>System</td><td>System of Systems</td></tr>
<tr><td>Sicard et al. [63]</td><td>Component</td><td>Sub-System</td><td>Machine</td><td>Manufacturing Line</td><td>Factory</td><td>-</td></tr>
<tr><td>Villalonga et al. [64]</td><td>Local</td><td colspan="3">System</td><td>Global</td><td>-</td></tr>
<tr><td>Chuang et al. [65]</td><td>IoT / Sensor</td><td>-</td><td>Operation</td><td>Process</td><td>-</td><td>-</td></tr>
<tr><td>Yang et al. [66]</td><td>Unit</td><td colspan="4">System</td><td>System of Systems</td></tr>
<tr><td>Finke et al. [67]</td><td>Sensors</td><td>-</td><td>Machine</td><td>Machine groups</td><td>Factories</td><td>-</td></tr>
<tr><td>Mendonça et al. [68]</td><td>Part / Component</td><td colspan="3">Subsystem</td><td>System</td><td>System of Systems</td></tr>
<tr><td>Latsou et al. [69]</td><td>Module</td><td colspan="3">Equipment</td><td>Factory / Enterprise</td><td>-</td></tr>
<tr><td>Hwang and Noh [70]</td><td>Unit</td><td>Module</td><td>Equipment</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Qian et al. [71]</td><td colspan="3">Units</td><td>Production Line</td><td>Workshop</td><td>-</td></tr>
<tr><td>Helmann [72]</td><td>-</td><td>-</td><td>Specific Machine</td><td>Factory Unit</td><td>Factory</td><td>-</td></tr>
<tr><td>Julien and Martin [53]</td><td>Component</td><td colspan="3">Equipment</td><td>System</td><td>System of System</td></tr>
<tr><td>Liu et al. [51]</td><td>-</td><td>Device</td><td>Unit</td><td>Production Line</td><td>-</td><td>-</td></tr>
</table>

TABLE 4. Visibility of digital models.

Author	White Box	Grey Box	Black Box
Brennan and Lesage [11]	Physics Based	-	Data-Driven
Aivaliotis et al. [74]	White Box	Grey Box	Black Box
Ouahabi et al. [75]	Physics-Based	Hybrid	Data Driven
Bellavista and Di Modica [76]	Simulation-Based	Hybrid	Data-Driven
Borangiu et al. [77]	Model-Driven	Combination	Data-Driven
Langlotz et al. [78]	Physics-based	Hybrid	Data-Driven

Kober et al. Lastly, Lugaresi and Matta distinguish between full- and part type traceability of a bill of material [85], which is an example for the fidelity of a model. We therefore propose to categorize digital models in two dimensions: The visibility (white box, grey box or black box) and the fidelity, which has the dimensions tolerance, frequency, and latency. Tolerance describes in this context the numeric difference between the parameter of the physical twin (PT) and the digital model. Frequency describes the number of updates in a specific time frame and latency the time, which lies between the change of a parameter in the physical twin and in the digital model.

D. DIGITAL THREAD

The categorization created by Kritzinger et al. into digital models, digital shadows and digital twins [6] is used by several authors [62], [86], [87], [88], [89], [90]. The differentiation is done according to the connection between the digital model, shadow, or twin and the physical twin. Barbieri use additional a pre digital twin [91] and Farghaly and Soman a digital mirror [92]. Similarly, Barbosa et al. distinguish between a digital copy, one directional data flow to the digital copy and two directional data flow [93]. Mendonça et al. use no data, one way interconnected and two way interconnected [68]. Webb et al. distinguish between one way and bidirectional data flow [18]. Webb et al. name a digital replica, additionally to DM, DS and DT, but do not describe it further [18]. Hengelbrock et al. differentiate between different levels of models, namely steady state, dynamic and validated, the next three levels are DS and DT [94]. Since there is no consistent differentiation feature, this categorization is not used in this work. Therefore, we use the three integration levels as proposed by Kritzinger et al. in this work. But as stated above, we think that the formalized definitions of Barbie and Hasselbring are more suitable.

The digital thread can also be defined according to its synchronization procedure. Park et al. distinguish between footprint and snapshot synchronization [95]. Footprint synchronization relies on historical and log based data over a period of time for monitoring and tracking, focusing on past performance and trends. In contrast, snapshot synchronization captures and uses data from a specific point in time, enabling real time simulation based functionalities and immediate status assessments. Since both of these refer to a specific use case, we will not use it in our taxonomy. Julien and Martin use synchronous and asynchronous synchronization [53]. According to them, synchronous synchronization can be either real time, near real time or periodic, which we see as a part of the fidelity of the digital model. Asynchronous synchronization can be event based, conditional or on demand. Böttjer et al. distinguish between continuous updates, event based updates and time based updates [73]. Continuous means real time in this context. Therefore, we see the categories continuous and time based already covered from the frequency dimension of the fidelity of the digital model. Sommer et al. categorize parameter based, partial structural and full structural [96]. Structural means, that the structure of the model has to be changed (partially), not only the parameters. We summarize the aforementioned and will use the following two dimensions of the synchronization procedure:

- **Update Strategy:** The update strategy can be either synchronous or asynchronous, while an asynchronous update strategy can be event based, conditional or on demand.
- **Scope:** Every update has a scope. We add the category of partial parameter based updates, which only update a part of the parameters, while the full parameter based update updates all parameters. This can be used additional to the categories from Sommer et al. namely partial structural and full structural [96].

Another way to distinguish different types of digital threads is the used network and communication protocol. Webb et al. categorize into wireless and wired industrial networks and name the IoT protocols MQTT, HTTPS, OPC-OA and OPC [18]. Additionally, they state there are other IoT protocols. Since there are other kinds of IoT protocols and new ones may arise, we don't use it for our taxonomy. But we will use the industrial network, either wireless or wired, since it has an impact on the structure of the DT system and can be clearly distinguished.

E. DEPLOYMENT

The structure of the DT can be distinguished in several ways. One way is the deployment. Yang et al. state edge and cloud twins [97]. Additionally, Bellavista and Di Modica state that the DT can be deployed on IoT devices [76]. We propose to use the complete categorization of Bellavista and Di Modica:

- **IoT Twins:** Employ lightweight models of specific components and conduct big data processing and local control with a focus on low latency and high reliability
- **Edge Twins:** Situated at plant gateways, which offer higher level control functionalities and orchestrate internet of things (IoT) sensors and actuators within a production locality.
- **Cloud Twins:** Engage in time consuming, typically off line parallel simulation and deep learning processes. May provide the edge twin with pre elaborated models.

F. FEATURES OF DIGITAL TWINS

This section is meant to give an overview of the different features and applications of digital twins. Although these are technically different, some authors have used them synonymously. As an example, Mohamed and Al-Jaroodi distinguish, besides other, between prediction and equipment diagnostic analysis. Related categorizations are: Huang et al. have categorized applications in the categories regarding the optimized key performance parameter, namely productivity, availability, quality [98]. Renard et al. categorized the applications regarding the gain, namely design / optimization gains, operational gains and decision-making gains [99]. Grigoriev et al. categorized into problems of engineering activity, complete solutions of tasks and tasks of operating activities [100]. West et al. use the categories supported business functions, service classification, lifecycle, environment, capabilities / level of delegation, decision-making horizon [101]. Jyeniskhan et al. categorized according to the hierarchy levels factory level, machine level, process level, product level and people [102]. Quahabi et al. stated different optimization objectives, namely time related, energy related, cost related, worker related and resource / operation related [86].

To categorize the features, we use the autonomy level. Several authors have used this, to distinguish between different types of digital twins. Villegas et al. used the categories predictive, prescriptive and autonomous [54]. Altmiranda and Colina created the categories stand alone — disconnected (level 0), integrated — descriptive (level 1), adaptive — diagnostic (level 2), intelligent — predictive (level 3), intelligent — prescriptive (level 4) and autonomous (level 5) [103]. Dolgov et al. categorize predictal, classical, adaptive and smart twins [104]. Dani et al. use the categories basic, 3D, digital twin and augmented [105]. Latsou et al. distinguish between manual, semi-automatic and fully automatic twins [69]. Mawson et al. used the application categories descriptive, predictive, prescriptive and control [106].

Dolgov et al., Dani et al. and Latsou have used categories, which are not clearly defined by its name, for example a smart twin, a basic twin or a semi-automatic twin. Therefore, we will not use their categorization. A disconnected digital twin, as stated by Altmiranda and Colina, is a digital model, according to our understanding. Therefore, we will not use this category. We define the five autonomy categories descriptive, diagnostic, predictive, prescriptive and autonomous. We do not use levels in this categorization because a higher level indicates a higher complexity of the digital twin, while several other factors influence it. For example, a diagnosis based on physical principles might be more complex than a prediction based on historical data, utilizing a black box model. Table 5 shows the categories as well as a question, which fits to the category. Furthermore, examples of features of DTs, which refer to the category, are shown.

G. SUMMARY

After the different dimensions, in which we categorize digital twins, were defined in the last subsections, we will summarize these in this section. A graphical summary is shown in Figure 9. First, we do not use specific life cycle phases, but we differentiate between the types digital template, digital twin prototype and digital twin / digital shadow, as proposed by Barbie and Hasselbring [7]. All of them can be used in different life cycle phases of the physical twin and have different characteristics. Furthermore, digital twins and digital shadows can be applicable in one or several

TABLE 5. Feature categories of digital twins.

Category	Question	Examples
Descriptive	What has happened?	Actualize [107] Augment [44] Compare [108] Conceptualize [53] Describe [109] Develop [72] Display [72], [76] Evaluate [110], [111] Identify [26] Inform [112] Interface [113] Model [17], [113] Monitor [14], [72], [76], [100], [113]–[117] Operate [112] Present [18] Recondition [72] Remote [76] Represent [95] Scale [68] Track [110] Virtualize [16], [95], [118] Visualize [18], [26], [44], [115], [116]
Diagnostic	Why has it happened?	Analyze [16], [18], [48], [53], [76], [117], [119] Diagnose [17], [78], [108], [112], [113], [118], [120] Inspect [18] Predict [114], [117] Supervise [120] Support [112] Troubleshoot [113]
Predictive	What might happen?	Cognize [53] Compare [53] Design [17] Detect [114] Model [121] Optimize [76] Predict [16]–[18], [26], [44], [53], [72], [75], [78], [95], [98], [107]–[110], [110], [114], [117]–[120], [122] Reduce [76] Sense [121] Simulate [18], [44], [53], [72], [95], [100], [108], [110], [111], [119], [120]
Prescriptive	What should happen?	Assist [116] Calculate [100] Design [110], [114] Develop [100] Dispatch [14], [116] Form [100] Improve [78], [119] Manage [18] Optimize [14], [17], [18], [44], [48], [53], [75], [111], [114]–[116], [122] Plan [75], [110], [116], [118], [119] Prescribe [107], [109] Prevent [114] Ranking [111] Schedule [17], [18], [116]–[118] Support [72], [110]
Autonomous	What will happen?	Act [112] Collaborate [53], [112] Collect [68] Control [17], [26], [53], [98], [98], [112], [114], [116], [118], [120], [121], [123] Customize [115] Decide [112] Manage [14], [100], [108], [116] Operate [14] Optimize [111], [114] Position [110] Search [68] Share [68] Tailor [121]

of the life cycle phases production, integration, operation, and end of life. A comparison to the life cycle phases we could found is stated in Table 1. Digital twins can be applied in six different domains. Each domain refers to a different type of physical twin, which is the counterpart of the digital twin: Product, production, human, resource, process, environment. A More detailed description and literature which uses the exact category can be found in Table 2. Besides the domain, the hierarchy level of the physical twin can be used to describe the digital twin. We use the hierarchy levels field device, control device, station, work centers, enterprise and connected world as in the RAMI 4.0 [8], but without the product category. It is compared with several other hierarchy level categorizations in Table 3.

The digital model, which is a component of the digital twin, can be categorized by its visibility into white box, gray box and black box (see Table 4). We further identified the following types of white- and gray box models: Geometry, equation, behavioral model, rule model. Another way to categorize digital models is their fidelity, which has the dimensions tolerance, frequency, and latency. In contrast to other authors, we don't distinguish between digital models, digital shadows and digital twins as different types of the same concept. There is a fundamental difference between digital models on one Hand and digital shadows or digital twins on the other [7]. We distinguish different types of digital threads, which can be either uni- or bidirectional. Furthermore, the digital thread can have different update strategies, namely synchronous or asynchronous. Asynchronous update strategies can be event based, conditional or on demand. They also differ in their scope, which can be partial or complete and parameter based or structural. The last dimension, in which digital threads can be categorized, is if it is wireless or wired. Another way to categorize digital twins is the way they are deployed. We identified IoT twins, edge-twins and cloud twins. We identified the following five autonomy categories, in which features and applications of digital twins can be sorted: Descriptive (What has happened?), diagnostic (Why has it happened?), predictive (What might happen?), prescriptive (What should happen?) and autonomous (What will happen?).

VI. TAXONOMY FOR DIGITAL TWINS IN MANUFACTURING

In the next step, we will examine objects for these characteristics and dimensions. We identify the objects by snowballing the literature, which was used to create the first taxonomy, as well as searching for "Digital Twins", "Manufacturing" and the characteristic in Google Scholar. The complete categorization of the papers is available in [24]. We found the following:

- Although we found implementations for nearly every stated category, those are not mutually exclusive. Most implementations take several dimensions into account. For example, Yang et al. implemented a digital twin from a spraying production line and also consider the product, the process, and the environment [124]. Barbie et al. implemented a DT and a DTP for underwater robots, which are considered the product, and also consider the environment, in which the robot is operating [125]. However, we identified the implementations to be either product-centric or production-centric. We therefore propose to use those two categories. This might be extended, if there are human-, resource-, process- or environment-centric implementations.
- Other than in the hierarchy levels which are derived from the RAMI 4.0 model, most DTs cannot be categorized by a single hierarchy level. A DT on the work center level is usually a combination of several station level models, which might consist of several control device level models, depending on the used data. We therefore propose to categorize according to the maximum hierarchy level. By doing so, it is an indicator for the complexity of the DT as well as the used data sources, while the categories are mutually exclusive.
- Li et al. implemented a DT for the key parameter prediction and optimization of a cold steel rolling machine [126]. They call it an IoT based framework.

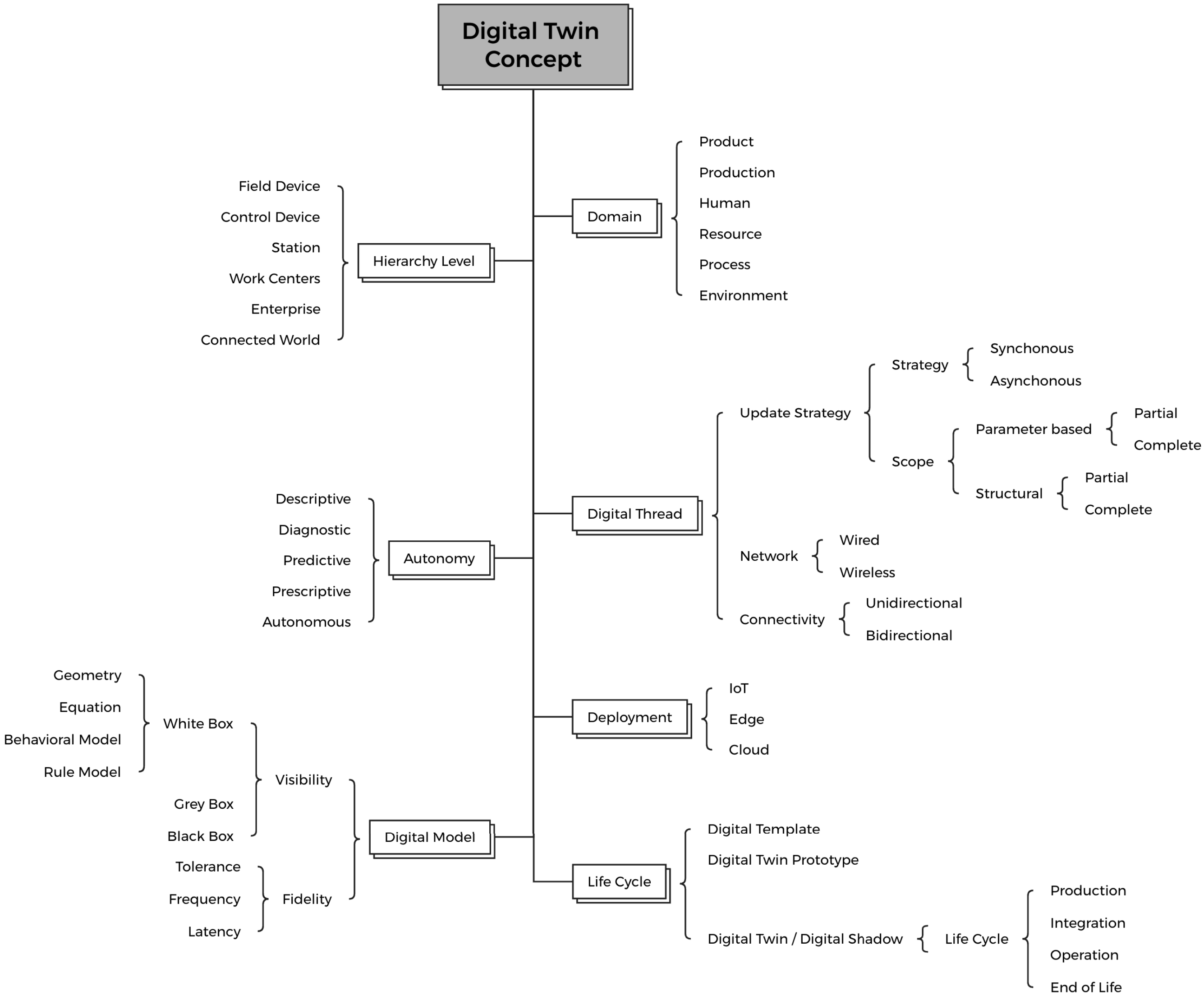

FIGURE 9. Initial categorization of digital twins in manufacturing.

Nevertheless, the DT is partially deployed on an edge device and partially in the cloud, not on the IoT devices. In fact, we were unable to find implementations of DTs, deployed on IoT devices. IoT devices can communicate via the internet, which is used to connect them with other hardware, on which the DT is deployed. We will therefore not use the category IoT in the deployment dimension. In our definition, IoT twins use the internet as digital thread to connect the different components of the DT.

- Li et al. created a framework, which is partially deployed on edge devices and partially in the cloud [126]. But while the edge devices are used for data fusion or feature extraction, among others, the models used for the resource intensive tasks like rolling force prediction or the tension optimization module, are deployed in the cloud. We define this as a cloud deployed twin because the digital model is deployed in the cloud. We see the edge devices as a part of the digital thread, which connects the physical twin with the digital twin. Even if there is data stored at the edge because the digital model is a core component of the DT or DS.
- Yang et al. also deployed the DT, which they call edge cloud digital twin, on edge devices as well as in the cloud [97]. They separate between the workshop based DT and the factory level DT. The workshop DT, which is deployed at the edge and is used for workshop job shop scheduling. The factory level DT is deployed in the cloud and used for factory wide scheduling tasks. Furthermore, the edge devices are connected wireless to the physical twin and the cloud is connected to the edge devices by wire. We define this as a multi-DT system, since there are two separate DTs: An wireless, workshop level edge twin and a factory level cloud twin, each with

its own digital model. But to categorize the digital thread of the cloud twin, we add the category hybrid to the network dimension of our taxonomy. This type requires equipment for wireless and wired networks.

- Most of the digital twins we found provide multiple features, which can be categorized into different autotomies. For example, a simulation in a DT can display the process, which is a descriptive feature. But it can also be used to analyze the process, which is a diagnostic feature, and to predict future states. As long as DTs provide more than one feature, this category cannot be mutually exclusive. We will therefore remove it from our taxonomy but propose to use it to categorize DT features.
- We found that several digital models could not be categorized into only one model type. For example, Pires et al. implement a DT which uses a DES, which is a behavioral model, and combine it with a mathematical formula to calculate the profit [127]. We therefore will not use this dimension in our taxonomy.
- We identified two types of DTs / DSs, which were implemented, regarding its life cycle. Product-centric twins tend to show the whole life cycle of its physical twin. Implementations of digital templates or digital twin prototypes were also product-centric. For Example, Zhang et al. implemented a digital twin of a multistage pump, which tracks the information about the pump during design as a digital template and a DT/DS in production, integration, and operation [58]. On the other Hand, production-centric DTs mostly are only applied to the operation phase of a production [16], [127], [128]. Therefore, a more detailed classification of the life cycle phase of production-centric DTs or DSs is not necessary, since it is usually just the operation phase. And for product-centric DTs it is not mutually exclusive, since the aim is to track the complete life cycle. We will therefore not use this dimension in our taxonomy.
- We could not define the digital thread of digital templates because there is no physical twin and therefore no connection to it. In fact, a digital template is only a collection of all information, needed to create the physical twin [7] and does therefore not fall into the digital twin paradigm. Only if this information is used to build the digital twin and to track it over its life cycle, in which case it would be the digital twin with a digital thread. We therefore will not use the category in our taxonomy.
- We furthermore found that the digital thread is not well defined for most implementations. We did not find any implementation for partial- or complete structural updates or complete parameter based updates. But from the fourteen reviewed implementations, only in two cases the update scope was stated at all, and those were implemented in the same paper. For the strategy, four out of fourteen implementations are documented and for the network five out of fourteen.

Based on these findings, the taxonomy is adapted. The second version is stated in Figure 10. The digital twin concept can be categorized according to their hierarchy level (Field device, control device, station, work centers, enterprise, connected world). Only the highest level which is displayed by the digital model, is used. In the domain dimension, we identified product-centric and production-centric implementations. Each of these dimensions might take other domains like humans, environment, resources, or the other one into account, but its focus lies on either the product or the production. Furthermore, the model can either be deployed on edge devices or in the cloud, and we distinguish between digital twin prototypes and digital twins / digital shadows, depending on its connectivity. Further categorization can be done by reviewing the digital thread and the digital model, which are important components in the digital twin concept. The digital thread has an update strategy, which can be either synchronous or asynchronous, and the update scope can be parameter based or structural, each either partial or complete. The network, which connects digital and physical twin, can be wired, wireless or hybrid and the connectivity can be uni- or bidirectional, depending on whether it is a digital twin or a digital shadow. The digital model can be categorized by its visibility (White box, gray box or black box) and its fidelity, which has the categories tolerance, frequency, and latency).

Since there were changes in the taxonomy, we start another iteration, where we choose the conceptual-to-empiric approach. We therefore use the second version of the taxonomy, to categorize the implementations found in the last iteration. To improve readability, we split the categorization into three tables. Table 6 shows the categorization of the domain, hierarchy level and life cycle. Every paper can clearly be categorized according to this, and implementations for every category could be found. Only for the implementation of Riedelsheimer et al., which is about an abstract "smart product" [129], no hierarchy level could be defined.

Table 7 shows the category according to the digital thread. While the connectivity of the implementations could be clearly defined, update strategy, scope, and network is not described for most implementations. Implementations for unidirectional and bidirectional connections were found. We also found implementations for wireless- and hybrid networks. Since for most implementations the network type is not named explicitly, presumably some of them use a wired network. We also found implementations for every update strategy, nevertheless most of the implementations are not described properly. The same is for the update scope, while we could not find implementations for every category. Only Barbie et al., who implemented a digital twin prototype for ocean observation systems, completely described their digital thread. Presumably, other implementations also have an update strategy and an update scope, but the authors missed describing it in their publication.

Table 8 categorizes the digital model and the deployment. Except for Riedelsheimer et al., the model visibility could

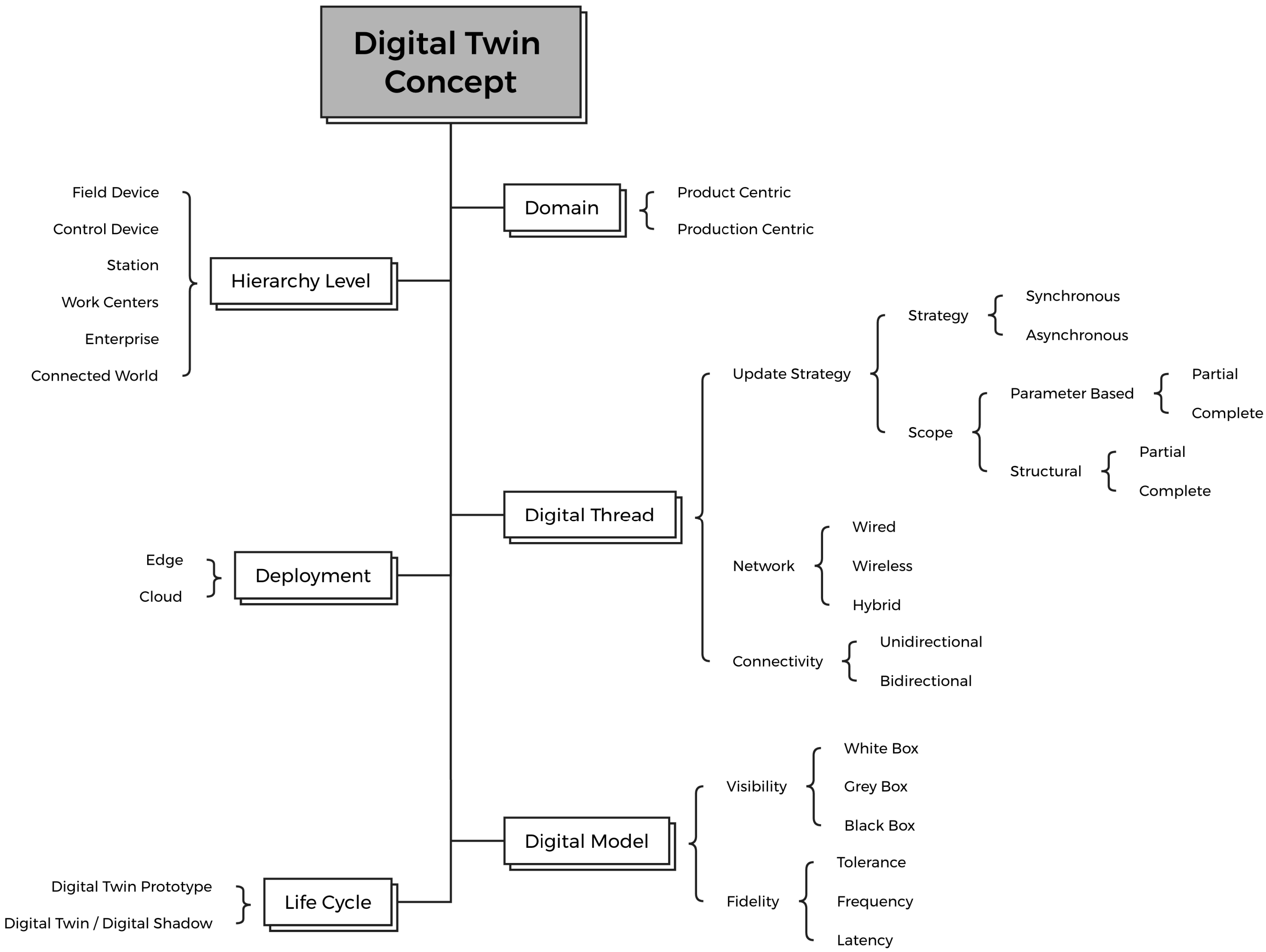

FIGURE 10. **Updated taxonomy of digital twins in manufacturing.**

be defined for every implementation and for every category an implementation were found. Most of the implementations also stated the deployment and for both types of deployment implementations were found. Regarding the model fidelity, most implementations could not be categorized according to their tolerance, frequency, and latency of the digital model. As for the dimensions of the digital thread, we presume that the models can be categorized in these dimensions, but the authors missed to describe these details in their publication.

To decide, if a third iteration of the taxonomy creating process should be done, we have to check if the ending conditions are met. We stated that our taxonomy should be the taxonomy should be concise, robust, comprehensive, extendable and explanatory. We will discuss these properties in the following.

- **Concise:** The taxonomy includes only key dimensions relevant for distinguishing digital twin implementations (e.g., hierarchy level, domain orientation, digital thread, digital model, deployment). Redundant categories were deliberately avoided, and the visualization (Figure 10) together with the standardized categorization tables ensures a compact representation.
- **Robust:** The taxonomy was successfully applied to a broad set of digital twin implementations (Tables 7 and 8). All works could be classified, even in cases where certain characteristics (e.g., update strategy or model fidelity) were not explicitly specified, demonstrating applicability under incomplete information.
- **Comprehensive:** The taxonomy covers essential aspects of digital twin implementations, including functional differences (digital thread vs. digital model), technical differences (network and deployment), and abstraction levels (product centric vs. production centric). The empirical analysis shows that almost all categories are represented by at least one implementation.
- **Extendable:** The modular structure of the taxonomy allows adding new categories without altering its overall design (e.g., additional network types or update strategies). The iterative development process leading

to the updated version (Figure 10) demonstrates its adaptability.

- **Explanatory:** The taxonomy facilitates analysis and comparison of implementations by providing unified terminology and classification criteria. Differences such as digital twin vs. digital shadow or edge vs. cloud deployment become transparent, and relationships between categories (e.g., update strategy and network architecture) are made visible.

Regarding the objective ending conditions, the taxonomy was not edited in the last iteration. Moreover, there is no dimension- or characteristic duplication. We further defined, that there should be at least one object classified under every characteristic under every dimension. This is not the case, since no publication stated the tolerance of the digital model, and we found no implementations for parameter-based partial updates and structural updates, whether partial or complete. But since there are very few publications which describe these aspects of the implementation, while we presume that we just could not find these categories. We are convinced that every digital model has a tolerance and every digital thread has an update Scope. We will therefore keep these categories and see all ending conditions as met.

VII. DISCUSSION

The results of this study provide a comprehensive overview of digital twins (DTs) in manufacturing, highlighting various categorizations, deployment strategies, and functionalities. However, several limitations and critical aspects must be considered.

A. LIMITATIONS OF THE LITERATURE SELECTION

This study focuses exclusively on digital twins in manufacturing. While this constraint ensures relevance within the industrial domain, it may overlook important insights from related fields such as healthcare, smart cities, and logistics, where digital twins are also applied. Additionally, the literature selection was limited to peer-reviewed journal and conference papers, excluding industry reports, industry standards, white papers, and other gray literature, which might contain valuable practical insights. However, in this way, we were able to make use of the knowledge of researchers, which focus their work on different aspects of the DT Concept.

B. METHODOLOGICAL CONSIDERATIONS

The use of retrieval augmented generation (RAG) significantly enhanced the efficiency of literature analysis. Nevertheless, it is important to acknowledge that despite the systematic approach, some relevant publications may have been overlooked. The search term was intentionally broad to capture various typologies, but the reliance on automated tools means that nuanced categorizations could have been missed. Moreover, RAG-based literature analysis is still an evolving field, and no fully standardized or validated tool was employed for this study.

To discuss the performance of the RAG-based literature search, we calculate the precision, recall and inter-rater-agreement. To calculate the precision, the relevant hits are divided by all hits, found by the RAG Agent. Since 144 studies were included in the creation of the first taxonomy and the RAG agent has 468 hits, the overall precision is $p_o = 144/468 = 0.31$. This value is relatively low, therefore the RAG agent showed numerous papers, which contained no categorization of DTs. But there were several steps used in the process. We also calculate the precision, based on the papers which were included after papers were sorted out based on the summary of the RAG agent. This is $p_m = 144/242 = 0.60$ which is significantly higher. Furthermore, 40 and therefore most of the paper which were excluded after the detail assessment, were excluded because the categorization was referenced. Explicitly telling the RAG agent, to not include referenced categorizations, might improve the result. Next, we calculate the recall, which is the number of relevant his out of all hits in the database. To get a rough estimate, ten randomly chosen papers in which the RAG agent has not found a categorization were checked manually. From the ten papers, 7 stated no differentiation at all [134], [135], [136], [137], [138], [139], [140]. Two mentioned the Differentiation between DM, DS and DT but without discussing it further [141], [142] and one names some benefits of DTs in the introduction without categorizing them. None of them would have been used in our taxonomy. We would have sorted them out because a differentiation between DM, DS and DT is probably based on the categorization from Kritzinger et al. and just naming benefits is not a categorization. We therefore argue, that at least most of the relevant literature was identified by the RAG agent.

To compare the literature search with RAG to a classical literature search, a full-text search has been made. In the PDF full texts, the word 'taxonomy' or one of the following synonyms is searched for: 'Classification', 'Categorization', 'Typology'. This leads to 391 hits. From the 146 papers, which have been used in this paper, 66 were not found, which is 45 %. From the 180 papers, which were discovered by the full-text search but not by the RAG agent, ten were randomly chosen and analyzed in detail. Seven of them contained no categorization of DTs at all [143], [144], [145], [146], [147], [148], [149]. Nickpasand and Gaspar named some features but did not categorize them [150]. Moreover, Al Faruque et al. stated different capabilities of cognitive DTs [151] and Pan et al. differentiated between edge- fog- and cloud DTs [152]. So, two out of ten of the papers found by a classical literature search, in which the RAG agent had not found a categorization, there is, in fact, a categorization included. To project this to all papers, we assume that from the 180 papers found by the full-text search but not by the RAG agent, 20% and therefore 36 papers contained a categorization. Then there would be a total of 182 papers

TABLE 6. Categorization of DT-Implementations regarding domain, hierarchy level and life cycle. Abbreviations: FD: Field Device, CD: Control Device, S: Station, WC: Work Center, E: Enterprize, CW: Connected World, DTP: Digital Twin Prototype, DT / DS: Digital Twin / Digital Shadow.

Author	Comment	Domain		Hierarchy Level						Life Cycle	
		Product-Centric	Production-Centric	FD	CD	S	WC	E	CW	DTP	DT / DS
Riedelsheimer et al. [129]		x		undefined							x
Cimino et al. [16]			x				x				x
Pires et al. [127]			x				x				x
Zhang et al. [58]		x			x						x
Yang et al. [124]			x				x				x
Vachalek et al. [128]			x				x				x
Yildiz et al. [130]			x						x		x
Barbie et al. [125]	Scenario A	x				x				x	
Barbie et al. [125]	Scenario B	x			x					x	
Židek et al. [131]			x	x							x
Yang et al. [97]	Workshop Level		x				x				x
Yang et al. [97]	Enterprise Level		x					x			x
Li et al. [126]			x					x			x
Siddiqui et al. [132]			x		x						x
Schwarz et al. [133]			x		x						x

TABLE 7. Categorization of DT implementations regarding the digital thread. Abbreviations: PP: Parameter Based Partial, PC Parameter based Complete, SP: Structural Partial, SC: Structural Complete, W: Wired, WL: Wireless, U: Unidirectional, B: Bidirectional.

Author	Comment	Update Strategy		Update Scope				Network			Connectivity	
		Sync	Async	PP	PC	SP	SC	W	WL	Hybrid	U	B
Riedelsheimer et al. [129]		undefined		undefined				undefined			x	
Cimino et al. [16]		undefined		undefined					x		x	
Pires et al. [127]			x	undefined				undefined			x	
Zhang et al. [58]		undefined		undefined				undefined			x	
Yang et al. [124]			x	undefined				undefined			x	
Vachalek et al. [128]		undefined		undefined				undefined			x	
Yildiz et al. [130]		undefined		undefined				undefined				x
Barbie et al. [125]	Scenario A	x		x					x		x	
Barbie et al. [125]	Scenario B		x	x					x		x	
Židek et al. [131]		undefined		undefined					x		x	
Yang et al. [97]	Workshop Level	undefined		undefined					x		x	
Yang et al. [97]	Enterprise Level	undefined		undefined						x	x	
Li et al. [126]		undefined		undefined				undefined			x	
Siddiqui et al. [132]		undefined		undefined				undefined			x	
Schwarz et al. [133]		undefined		undefined				undefined			x	

TABLE 8. Categorization of DT-Implementations regarding the digital model and the deployment.

Author	Comment	Model Visibility			Model Fidelity			Deployment	
		White Box	Grey Box	Black Box	Tolerance	Frequency	Latency	Edge	Cloud
Riedelsheimer et al. [129]		undefined			undefined			x	
Cimino et al. [16]		x			undefined				x
Pires et al. [127]		x			undefined	high	low	undefined	
Zhang et al. [58]		x			undefined			undefined	
Yang et al. [124]		x			undefined	50 ms	undefined	undefined	
Vachalek et al. [128]		x			undefined			undefined	
Yildiz et al. [130]		x			undefined				x
Barbie et al. [125]	Scenario A	x			undefined	variable	undefined		x
Barbie et al. [125]	Scenario B	x			undefined	on demand	undefined		x
Židek et al. [131]		x			undefined				x
Yang et al. [97]	Workshop Level	x			undefined			x	
Yang et al. [97]	Enterprise Level	x			undefined				x
Li et al. [126]		x			undefined				x
Siddiqui et al. [132]				x	undefined	high	low	x	
Schwarz et al. [133]			x		undefined				x

containing a categorization, including those used in this paper. Then the recall for the RAG agent can be calculated to $r_{RAG} = 182/144 = 0.79$ and for the full-text search $r_{fulltext} = (182 - 66)/182 = 0.63$. Furthermore, we can calculate the precision of the full-text search to $p_{fulltext} = (182 - 66)/391 = 0.29$. The metrics are summarized in

TABLE 9. Comparison of quality metrics for different methodologies.

Methodology	Precision	Recall
RAG without manual screening	0.31	0.79
RAG with manual screening	0.60	0.79
Full-text search	0.29	0.63

Table 9. The precision of the RAG agent combined with a manual screening of the created summaries is about twice as big as for RAG without screening and the full-text search. Furthermore, the recall of the RAG technology is about 25% higher as for the full-text-search. This shows the potential of RAG for literature search, although these are only rough values.

We also calculated fleiss'kappa, to evaluate the inter rater agreement between the different RAG agents during the literature search. The calculation can be found in [24]. The kappa of 0.36 indicates that there is a fair agreement between the agents and there is a lot of space for improvement. This might be due to the reason that we used four different RAG configurations. Nevertheless, improving the methodology might improve precision and recall. Therefore, further research should be done, evaluating and improving this method.

Not every categorization, which was found, could be used in this paper. 24 Categorizations are too specific to their use case, so they could not be integrated in our taxonomy [13], [153], [154], [155], [156], [157], [158], [159], [160], [161], [162], [163], [164], [165], [166], [167], [168], [169], [170], [171], [172], [173], [174], [175]. Ten categorizations were not used because the dimensions hierarchy and domain were mixed [41], [176], [177], [178], [179], [180], [181], [182], [183], [184]. Specific applications were not considered in the taxonomy. Therefore, four categorizations of applications were not used [3], [174], [185], [186]. Nevertheless, a large portion of the identified distinctions were considered in the taxonomy. Therefore, it represents a synthesis of the work of many researchers in the field of digital twins.

C. EVALUATION OF THE RESULTS

The proposed taxonomy successfully provides a structured overview of DTs in manufacturing. It consolidates different categorizations from literature and integrates them into a unified framework. However, the taxonomy is not infinitely extensible. New technologies, evolving industrial standards, and novel applications may necessitate periodic updates. Furthermore, while the taxonomy is useful for classification, its applicability for assessing real-world implementations remains to be tested. Future research should explore how this taxonomy can be applied to classify and analyze specific case studies or industrial implementations of DTs.

Additionally, the taxonomy offers practitioners a valuable orientation guide, helping them to identify key aspects that need to be considered when implementing a digital twin in a specific industrial setting. By outlining essential dimensions such as life-cycle phases, hierarchy levels, and digital thread configurations, the taxonomy aids in structuring the decision-making process and ensuring that critical factors are addressed during implementation. Furthermore, the categorizations which have been identified can be used to start a search for relevant literature about and certain aspect of a DT.

VIII. CONCLUSION AND FUTURE WORK

This study presents a structured taxonomy of digital twins in manufacturing, integrating various perspectives from existing literature to create a comprehensive classification framework. The taxonomy provides a systematic approach to categorizing DTs based on life-cycle phases, hierarchy levels, digital model characteristics, digital thread configurations and deployment strategies.

The findings contribute to both research and practice by offering a reference model that facilitates the understanding and development of digital twins. Researchers can use the taxonomy as a foundation for further theoretical investigations and refinements, while practitioners can leverage it to guide the implementation of digital twin solutions in industrial environments.

Despite its contributions, the study has some limitations, particularly regarding the reliance on AI-based literature analysis and the exclusion of non-peer-reviewed sources. Future research should focus on validating the taxonomy further through more systematic empirical studies or real-world case analyses. We will use it to map implementations of digital twins, to show active fields of current research. Furthermore, as digital twin technology continues to evolve, the taxonomy should be periodically updated to reflect emerging trends, novel architectures, and new industrial applications.

Ultimately, this taxonomy serves as a crucial step towards a more structured and standardized understanding of digital twins in manufacturing, promoting both academic discourse and practical adoption.

APPENDIX

A. RAG CONFIGURATION DETAILS

The Retrieval-Augmented Generation (RAG) framework was configured using the following parameters:

- **Embedding Model: GPT4AllEmbeddings** [187]; encodes textual input into dense vector representations for similarity search and retrieval.
- **Generator Model: LLaMA 3.1 70B**; autoregressive language model that produces the final responses based on query and retrieved context.
- **Temperature: 0.2**; sampling parameter controlling the randomness of token selection during generation.
- **Maximum Output Length: 512 tokens**; upper bound on the number of tokens generated in a single response.
- **Top_p: 0.9**; nucleus sampling parameter restricting the candidate token pool to those with cumulative probability below the threshold.

The parameters **Chunk Size** and **Number of Chunks** define the segmentation of documents into token-based units and the number of such units retrieved per query, respectively. Four configurations were used:

1) Chunk Size: 500, Number of Chunks: 5
2) Chunk Size: 500, Number of Chunks: 10
3) Chunk Size: 1000, Number of Chunks: 2
4) Chunk Size: 1000, Number of Chunks: 5

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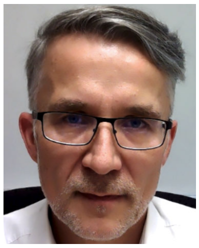

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