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Review

State of the Art and Future Directions of Digital Twins for Production Logistics: A Systematic Literature Review

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Abstract: Digital Twins (DTs) are widely discussed in the context of the Industry 4.0 paradigm as one of the main opportunities to strengthen the overall competitiveness of manufacturing enterprises. Despite a substantial scientific discussion, there is still no unified understanding regarding the constitution and subsequent usage of DTs within production logistics systems. Therefore, this paper focuses on the application of DTs in production logistics. The authors discuss common definitions, characteristics, and functionalities of DTs and outline current developments and implications from state-of-the-art implementation approaches, by using a systematic literature review. Moreover, based on the research findings, the authors evaluate a set of DT case studies, identify current research gaps, and present potential directions for future research initiatives regarding the field of production logistics in manufacturing enterprises.

Keywords: Digital Twin; modeling; virtual model; simulation; production logistics; systematic literature review

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1. Introduction

In today's hyper-dynamic environment, the Industry 4.0 paradigm is reaching far beyond the basic concepts of automation by revolutionizing manufacturing enterprises especially in the areas of smart production and smart logistics. Moreover, Industry 4.0 is characterized by the vertical and horizontal integration of production and logistics systems as well as the merging between the physical and virtual worlds [1]. Industry 4.0 approaches can, therefore, be divided into digitalization, digital interconnectivity, and self-controlling systems [2]. Various technologies and technological concepts are discussed in production logistics, which can be classified as Cyber-Physical Systems (CPS), Internet of Things (IoT), interfaces, decentralized applications, real-time localization systems, automatic identification, virtual environments including Digital Twins (DTs), and applications of data science such as machine learning, data mining, and big data analytics [3]. Companies are challenged with increasing dynamics, structural complexity, increased uncertainties and risks, and multiple feedback cycles. This leads to difficulties in the optimal design and control of production logistics systems [4,5]. However, DT technology offers several approaches to overcome these problems [6,7]. Originally, the concept of a Digital Twin was presented at the University of Michigan by Grieves in 2003. It was first introduced as a concept for product lifecycle management (PLM). At this stage, it was not explicitly called a Digital Twin, but the paper described the idea and important components of such a system [8]. NASA has taken up this concept and described a Digital Twin in the technology roadmap for their flight system, to make comprehensive diagnostics and prognostics, enabling continuous safe operations over the life cycle of the system [9]. Furthermore, Glaessgen and Stargel described a Digital Twin for the next generations of NASA and U.S. Air Force vehicles, giving more detail [10]. Nevertheless, different fields of research adapt the original concept of a Digital Twin to their specific domain. Therefore, several publications discuss the application of DTs in production planning and control, maintenance, process design, layout design, product design, production process optimization, as well as prognostics and health management (PHM) [11–13]. This may also be the reason why there is no common definition of a DT [14]. One approach to finding a standardized and common definition of DTs has been elaborated by the International Organization for Standardization (ISO). According to this proposal, the basic idea of a Digital Twin is to create a digital representation of an observable system or element [15]. More specifically, other authors suppose it to mirror a product, process, or service in virtual space [16]. Convergence between the physical and the virtual space is mandatory [17] to create a closed-loop interaction between these components [18]. A bidirectional communication enhances this convergence [17], as real-time data integration plays a key role for Digital Twins [19]. The concept of Cyber-Physical Systems (CPS) can be described similarly. Tao et al. compared the differences and correlations of the two concepts. DTs are often discussed in the engineering area and are more focused on virtual models (VMs) that enable one-to-one communication between physical and virtual parts. CPS on the other hand is more frequently discussed in the scientific area. To enable fusion and one-to-many communication between the spaces, CPS emphasizes 3C capabilities (computation, communication, and control) [20]. The DT technology can also be seen as a key enabler for realizing a Cyber-Physical Production System (CPPS) [21–23]. Among many other application areas, there is great potential for use in production logistics processes [3]. Nevertheless, the different views and possible applications of DTs in the various domains lead to the result that no common understanding is being formed for this technology and its potentials. This paper aims to achieve a clear delimitation of DTs for the area of production logistics, to analyze potentials based on a systematic literature review enabling discussion of the state of the art in this specific domain. In this regard, further developments in this area can be established based on the systematic evaluation of the current literature with a special emphasis on common implementation concepts. Furthermore, barriers and research gaps will be identified as a starting point for further research initiatives.

2. Materials and Methods

A systematic literature review was conducted to analyze current developments and the state-of-the-art for the use of Digital Twins in production logistics processes. As suggested by the guidelines for systematic literature reviews [24], first a database was chosen. Here, the Scopus database was used to find relevant and qualitative papers since other scientific databases like Web of Science showed no significant differences with the identified search results. To obtain a comprehensive data set for the analysis in this research, a broad search strategy was used, limiting the search terms to only the two focus areas of logistics and DTs. To fulfill the overall aim of this paper, the emphasis was placed on DT implementation and implementation concepts for DTs in this area. The search was limited to the document types of articles and conference papers as well as the subject areas of engineering and business, management and accounting. To elaborate on the current developments on this topic, the timeframe was limited to the years 2015 to 2021. The term Digital Twin* resulted in 2689 hits. When further limited to logistic*, 93 publications were found. The final query was formulated as follows: (TITLE-ABS-KEY (logistic*) AND TITLE-ABS-KEY (Digital twin*)) AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"cp")) AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"BUSI")) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015)) AND (LIMIT-TO (LANGUAGE,"English")). As displayed in Figure 1, the PRISMA method was used for the systematic literature review, although the method has been slightly adapted regarding a backward search as suggested by vom Brocke et al. [25,26].

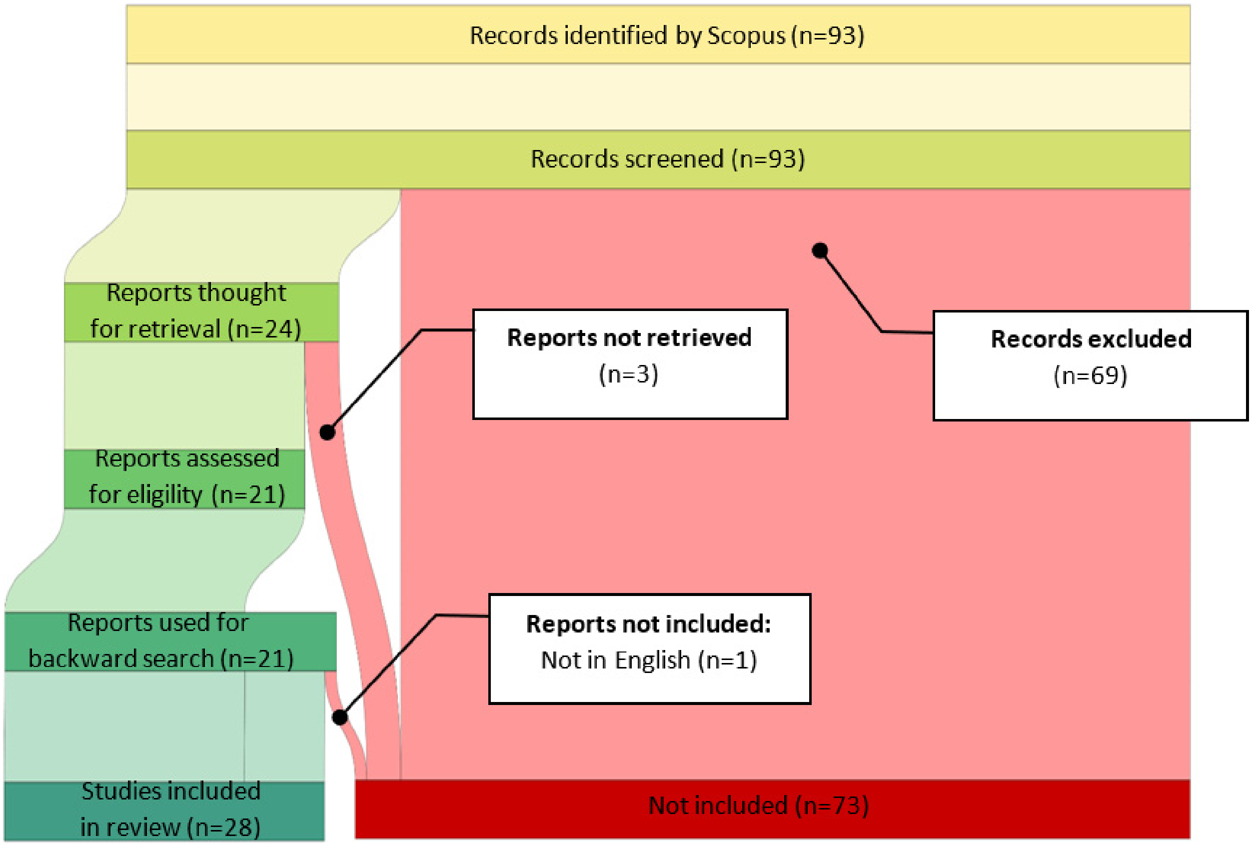

Figure 1. Sankey-based visualization of the PRISMA selection process [25,26].

First, the titles and abstracts of these publications were screened and rated as high-, medium-, and low-appropriate by two independent researchers. Papers with significant differences between these ratings were evaluated by a third researcher. If papers dealt with DT implementation or implementation concepts of DTs in production logistics, the paper was rated with high appropriateness. Papers dealing with DT implementation, or implementation concepts of DTs in other domains, were rated with medium appropriateness. If no DT is described or if the description did not fit into one of the categories, the appropriateness was rated low. High-appropriate papers were analyzed in full text. In addition, a backward reference search was performed via the CitationGecko online tool. Papers that are cited at least three times by the high-appropriate papers were also included in the full-text analysis.

3. Results

3.1. Descriptive Analyses

Table 1 shows the result of the rating process of the identified records. Of these, 24 papers were classified as high-appropriate, 23 as medium-appropriate, and 46 as low-appropriate. As many as 21 of the high-appropriate papers were available to the authors and, therefore, included in the further analyses.

Table 1. Rating of the screened records.

Appropriateness	Records	Records [%]
Total	93	100.00
High-appropriate papers	24	25.81
Medium-appropriate papers	23	24.73
Low-appropriate papers	46	49.46

Out of the screened records, no papers were published in 2015 and 2016. Five papers (5.38%) were published in 2017, eight papers (8.60%) in 2018, 27 papers (29.03%) in 2019, 42 papers (45.26%) in 2020, and 21 papers (22.58%) in 2021, up to the date of conducting the literature search. Publications from 2015 to 2020 are shown in Figure 2, indicating an increasing research interest in this topic.

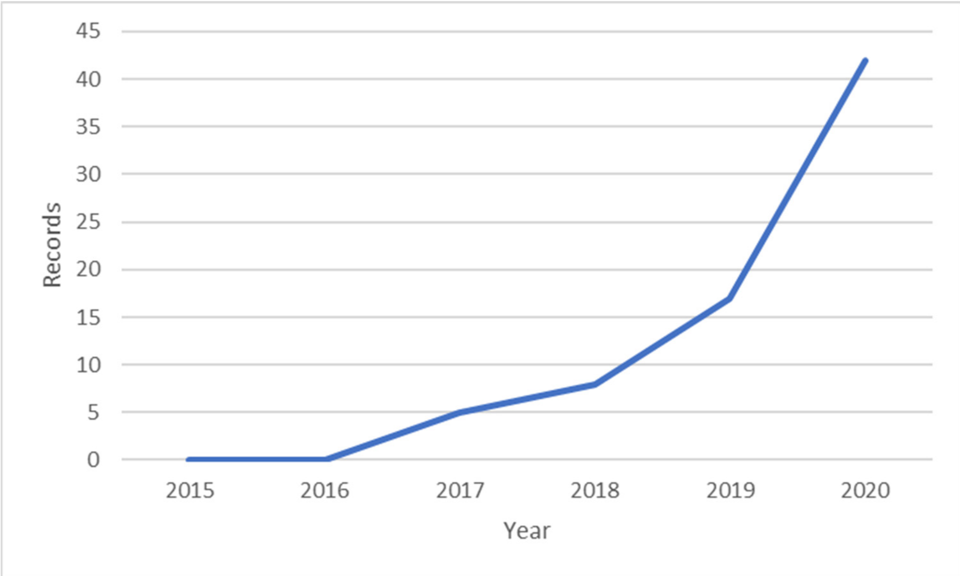

Figure 2. Identified records by year of publication.

Most often, papers within the defined limitations are published in Applied Sciences, Journal of Manufacturing Systems, Sensors, Academy of Strategic Management Journal, IEEE Access, IFAAC Papersonline, and Robotics and Computer Integrated Manufacturing, as noted in Table 2.

Table 2. Publication sources.

Source	Records	Records [%]
Applied Sciences Switzerland	5	5.38
Journal of Manufacturing Systems	4	4.30
Sensors	4	4.30
Academy of Strategic Management Journal	3	3.23
IEEE Access	3	3.23
IFAC Papersonline	3	3.23
Robotics and Computer Integrated Manufacturing	3	3.23
EAI Endorsed Transactions on Energy Web	2	2.15
International Journal of Computer Integrated Manufacturing	2	2.15
Procedia CIRP	2	2.15
Others	62	66.67

To identify research collaborations, the number of authors per publication was analyzed. The allocation of the number of authors is shown in Figure 3. A majority of 22 papers (23.66%) were written by four authors; 20 papers (21.53%) were written by three authors, 15 papers (16,13%) by two authors, eleven papers (11.83%) by six authors, 10 papers (10.75%) by five authors, six papers (6.45%) by one author, six papers by seven authors, two papers (2.15%) by eight authors, and one paper (1.08%) by nine authors. When directly searching for the term DT, the Scopus database identifies Tao F. as the author with the most records (41) in this general field. However, when searching for DT in production logistics in detail, Qu T. leads the list of authors with six records. All authors with at least three records in the area of interest are displayed in Figure 4.

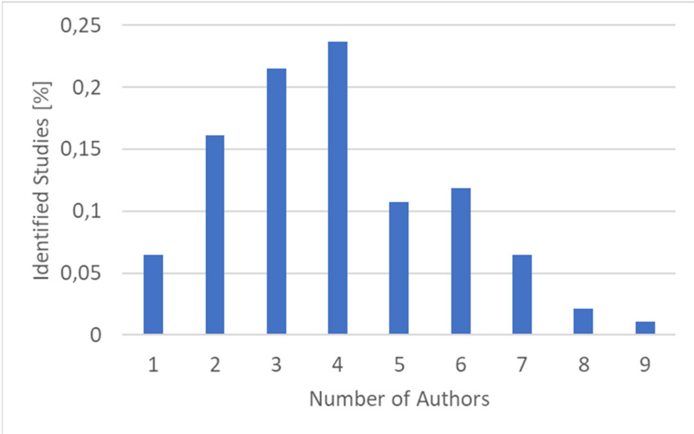

Figure 3. Research collaborations.

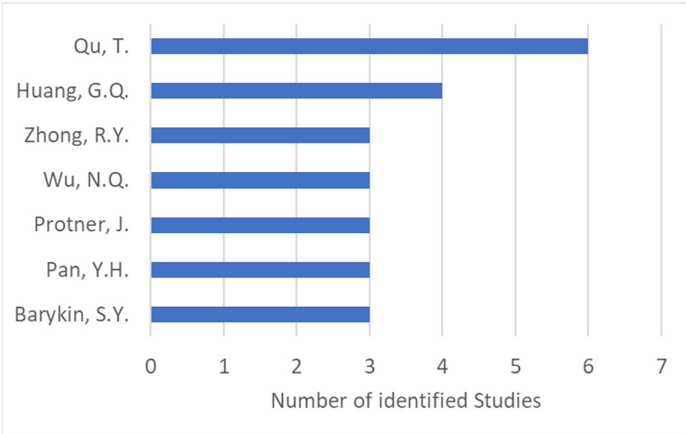

Figure 4. Records by author.

Figure 5 shows a heat map of the number of records by country to which the authors are assigned. In addition, Table 3 presents the countries to which at least three records are assigned. Most authors in this area are assigned to Germany (26), followed by China (14), the Russian Federation (9), and Hong Kong (8).

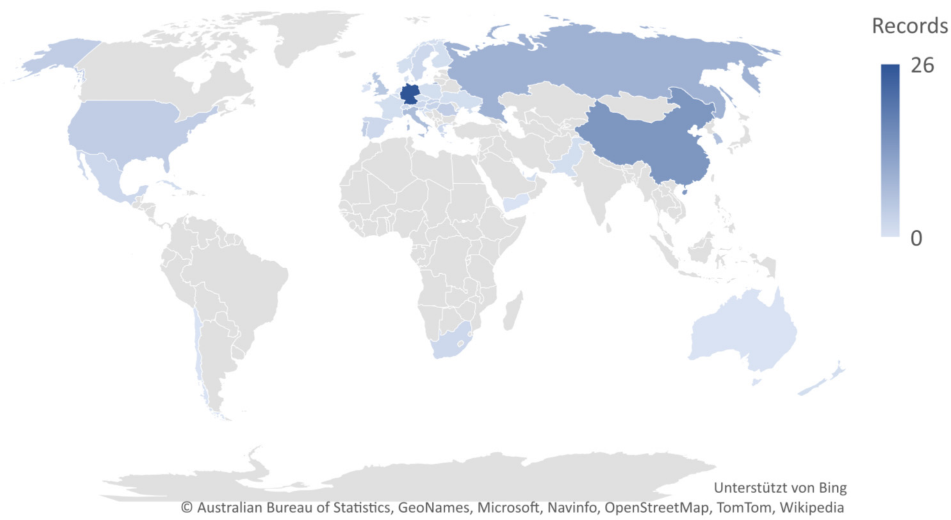

Figure 5. Heatmap of records by country.

Table 3. Records by country.

Countries	Records
Germany	26
China	14
Russian Federation	9
Hong Kong	8
Italy	7
South Korea	6
United Kingdom	5
United States	4
Portugal	4
Romania	4
Hungary	3
Slovakia	3
Slovenia	3

Although most of the authors can be attributed to Germany, they have varying affiliations. In the present case, most authors are affiliated with the University of Hong Kong (7), followed by the University of Jinan (6) in China. The institutions to which at least three records can be linked are listed in Table 4.

Table 4. Records by affiliation.

Affiliation	Records
The University of Hong Kong	7
Jinan University	6
Peter the Great St. Petersburg Polytechnic University	3
Otto von Guericke University of Magdeburg	3
Technical University of Cluj-Napoca	3
Univerza v Ljubljani	3
Macau University of Science and Technology	3
Southern University of Science and Technology	3

Index keywords and author keywords were analyzed, and the most used keywords are listed in Table 5. As expected, the keyword *Digital Twin* is most often used (index 56.99%, author 70.97%). Due to the described similarities to *CPSs*, it is unsurprising that this keyword is also part of the 10 most used keywords (index 16.13%, author 10.75%). Interestingly, among the index keywords, *manufacturing* (index 24.73%, author 4.30%) is used more frequently than *logistics* (index 11.83%, author 13.98%), whereas it is vice versa among the author keywords. *Supply chain management and control* is also part of the logistics domain and can also be found among the most frequently used keywords (index 10.75%, author 8.60%). A DT can be described as an *embedded system*, which is also one of the most frequently used index keywords (index 15.05%). *Simulations* are a key technology of DT, which is also reflected by the listed author keywords (author 18.28%). The frequently used keyword *Industry 4.0* (index 13.98%, author 17.20%) confirms the statement that DT technologies are an integral part of the discussion of this paradigm. The *decision-making and support* (index 11.83%, author 5.38%) capabilities of DTs are also part of these keywords, as well as enablers like *IoT* (index 10.75%, author 7.53%), and *big data* (author 6.45%). The intended use of DTs over the entire *life cycle* is indicated by the respective index keyword (index 15.05%).

Backward Reference Search

The seed papers of the high-appropriate papers are used as seed papers in the CitationGecko tool (www.citationgecko.com, accessed on 9 November 2021) to get a deeper understanding of the interconnections between them and ensure that no relevant literature is ignored in this review. As can be seen in Figure 6, most of the papers are directly or indirectly connected. Papers cited by at least three of the seed papers are included in the in-depth analysis. Based on this limitation, eight papers listed in Table 6 were assigned to this category, with one paper (ID 7) written in Chinese and, therefore, being excluded.

Table 5. Keyword analysis.

Index Keywords		Author Keywords	
Digital Twin	56.99%	Digital Twin (application)	70.97%
(Smart) Manufacturing (companies)	24.73%	(Discrete Event/Logistics/Factory) simulation (model)	18.28%
Cyber-Physical Systems	16.13%	Industry 4.0	17.20%
Embedded systems	15.05%	(Production/In-house/Digital/Smart/multi-modal) logistics (4.0)	13.98%
Life cycle	15.05%	Cyber-Physical (production) Systems	10.75%
Industry 4.0	13.98%	(Smart) Supply Chain (management /digitization/control)	8.60%
Decision-making	11.83%	Internet of Things (IoT)	7.53%
(Production) Logistics (processes)	11.83%	Big Data	6.45%
Supply Chains	10.75%	Decision (support/making)	5.38%
(Industrial) Internet of Things (IoT)	10.75%	Smart manufacturing	4.30%

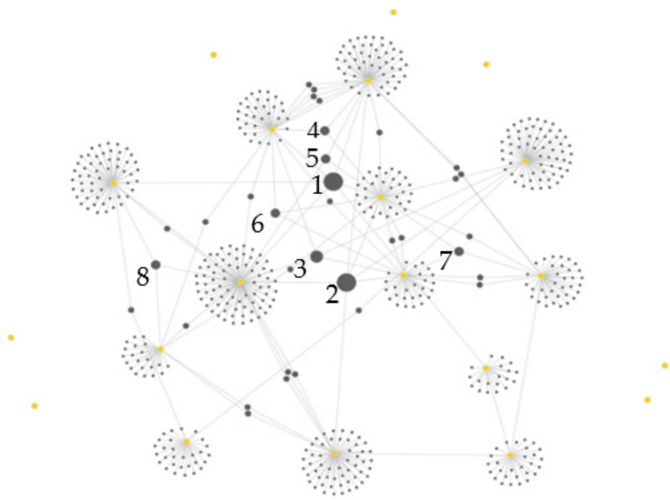

Figure 6. Reference graph.

Table 6. Results of backward reference search.

ID	Ref. No.	Authors and Year	No. of Citations
1	[17]	Tao and Zhang, 2017	5
2	[13]	Tao et al. 2018	5
3	[11]	Kritzinger et al. 2018	4
4	[22]	Zheng et al. 2019	3
5	[27]	Tao et al. 2018	3
6	[12]	Tao et al. 2019	3
7	[28]	Tao et al. 2018	3
8	[29]	Uhlemann et al. 2017	3

3.2. Content Analyses

The seven papers of the backward reference search and the 21 available high-appropriate papers were analyzed in full text. Table 7 shows an overview of these papers. The table shows the reference and the DT definition, as well as the technology used for creating a VM, the type of the paper, and their application domain. Used VMs in the considered papers are the Discrete Event Simulation (DES), a Multidisciplinary Design Optimization (MDO), Game Engines (GE) like Unity, Physical Simulations (PS), Analytical Models (AM), Time-Weighted Multiple Linear Regression (TWMLR), Catmull-Rom Splines (CRS), Agent-Based Simulations (ABS), a Knowledge Database (KD), and Automated Guided Vehicle (AGV) Simulators.

Table 7. Studies included in the review.

Ref. No.	Author and Year	DT Definition	Virtual Model	Type	Application Domain
[30]	Ceolho et al. 2021	Tao et al.	DES	case study	Distribution Center, Automotive
[31]	Guo et al. 2021	Tao et al.	DES	case study	Electronics
[32]	Jiang et al. 2021	Tao et al.	DES	case study	Aerospace
[33]	Pan et al. 2021	Tao et al.	MDO	case study	Paint Manufacturer
[34]	Vachalek et al. 2021	Grieves	DES	case study	Laboratory
[35]	Aglianos et al. 2020	Glaessgen and Stargel	-	review	-
[36]	Agostino et al. 2020	Glaessgen and Stargel	DES	case study	Automotive
[37]	Grigoriev et al. 2020	Grieves	-	concept	-
[38]	Hauge et al. 2020	Tao et al.	GE	case study	Laboratory
[39]	Hu et al. 2020	Tao et al.	PS	case study	Electronics
[40]	Makarova et al. 2020	other	DES	case study	Automotive
[21]	Sommer et al. 2020	other	DES	case study	not assignable
[41]	Wang and Wu, 2020	Glaessgen and Stargel	AM	case study	not assignable
[42]	Wang et al. 2020	Tao et al. Glaessgen and Stargel	TWMLR	case study	Metalworking
[43]	Herakovic et al. 2019	Tao et al.	ABS	case study	Laboratory
[44]	Nikolakis et al. 2019	Grieves	CRS	case study	Warehouse
[12]	Tao et al. 2019	Tao et al.	-	review	-
[22]	Zheng et al. 2019	Tao et al.	PS	case study	Metalworking
[45]	Krajcovic et al. 2018	other	-	case study	not assignable
[11]	Kritzinger et al. 2018	other	-	review	-
[19]	Kuehn, 2018	other	-	concept	-
[13]	Tao et al. 2018	Tao et al.	-	concept	-
[27]	Tao et al. 2018	Tao et al.	PS	case study	Energy
[46]	Yao et al. 2018	Grieves	DES/AGV Simulator	case study	Laboratory
[47]	Bottani et al. 2017	other	DES/AGV Simulator	case study	not assignable
[48]	Brenner and Hummel, 2017	other	KD	case study	Laboratory
[17]	Tao and Zhang, 2017	Tao et al.	-	concept	-
[29]	Uhlemann et al. 2017	other	-	concept	-

Due to the focus of this literature review, a majority of 20 papers are case studies (71.43%). Five papers can be classified as concept papers (17.86%) without implementations of DTs and three papers are literature reviews (10.71%).

3.3. Definitions of Digital Twins

To the best of the authors' knowledge, it can be stated that still no uniform definition of a Digital Twin [11,12,14,22]. To evaluate the state of the art of Digital Twins for production logistics processes, we first discuss which definitions are used in the high-appropriate papers. As shown in Figure 7, the five dimensions of Tao et al. (46.43%), the three dimensions of Grieves (14.29%), as well as the definition of Glaessgen and Stargel (14.29%) are commonly used; 28.57% of the papers used other or no definitions. In the following paragraphs, the three commonly used definitions are discussed in more detail.

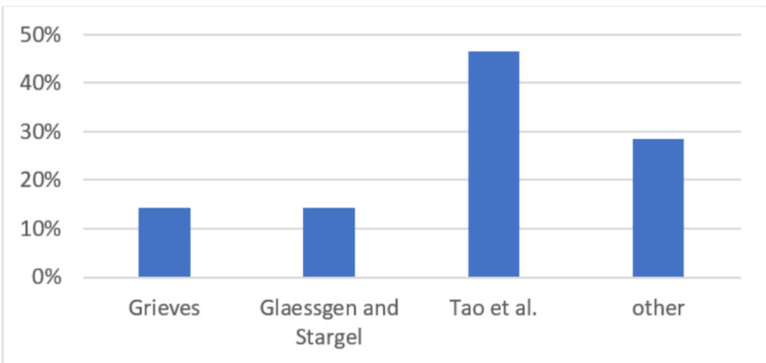

Figure 7. Definitions used for DTs.

3.3.1. Three Dimensions by Grieves

The definition by Grieves focuses on a new PLM paradigm. As mentioned above, at this stage the described system was not explicitly described as a DT, but was called a Mirrored Spaces Model. Nevertheless, this definition serves as the fundament of DT development. Grieves' model comprises three components: the "real space, virtual space(s), and a linking mechanism referred to as data, and information/process connection [of] real space and virtual space(s)" [49]. The real space is the physical object which can be observed via our senses. An additional virtual space entails the computer-created representation of the real world, which can be accessed and manipulated to evaluate alternative designs and the lives of those designs. The linking mechanism, as its name implies, links the virtual space with the real space, to substantially mirror the state of the real object in the virtual space. Therefore, the linkage must be robust, accurate, and timely [49].

3.3.2. Definition by Glaessgen and Stargel

The definition by Glaessgen and Stargel emerged from DT applications and developments for NASA and the US Air Force and is thus more focused on aviation vehicles.

Similar to Grieves, Glaessgen and Stargel also include the physical and the virtual world in their concept: "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin." [10]. The DT should mirror the real system in near-real-time to a virtual one, allowing the evaluation of the consequences of parameter modifications in not-foreseen situations. This capability is especially useful for a long-term space mission, in which failures of the system could have severe consequences [10].

3.3.3. Five Dimensions by Tao et al.

Building on and extending Grieves' definition, the one from Tao et al. has evolved from and is more focused on the manufacturing shop-floor perspective [13,23]. According to this definition, a DT has five dimensions: a physical entity, a VM, a service system, DT data, and the connection among these elements [27]. The physical entity is the real-world observable element of the DT, representing Grieves' real space. It may be a product, a physical system, process activities, as well as an organization [16]. Moreover, the physical entity can be divided into three levels of consideration, namely unit level, system level, and system of systems [13]. The VM mirrors the physical entity regarding geometry, properties, behavior, and rules [27]. The rule model within the VM is based on historical data or domain experts and enables conclusions, judgments, evaluations, and decisions for specific situations. The DT data include data from the physical entity (static attributes and dynamic condition data), the VM (simulation results), the provided services (data gathered from invocation and execution of the services), domain experts, as well as preprocessed data. Also included are the fusion data of the aforementioned resources [16]. The service system, as the fourth component, provides services for the physical entity and the VM. It is used to optimize the operations of the physical entity and adjusts parameter settings of the VM to ensure the validity of the model [27]. The last part of this definition is the bidirectional connection between all the listed elements to enable collaboration between them [16].

3.3.4. Similarities and Differences of DT Definitions

Grieves first described a DT with three dimensions and focused on PLM. Glaessgen and Stargel, however, defined a DT more generally, but with a strong focus on NASA and U.S. Air Force vehicles. Tao et al. took Grieves' three dimensions and expanded them with two additional dimensions: DT data and a service system, which enhances the functionality and generic application of the DT concept. Furthermore, they described the dimensions in detail and elaborated their characteristics. Among other uses, they explicitly adapted their definition to shop-floor systems, which contradicted the clear product focus of Grieves', and Glaessgen and Stargel's definitions and introduced the process perspective to DTs.

Overall, it can be summarized that all these definitions describe a VM that can mirror the functions, behavior, and state in near real-time of a physical entity. This VM can be used to predict future states, evaluate different scenarios or parameter settings, adapt to unforeseen situations, and optimize the physical entity. The insights gained from the VM are used to intervene in a controlling manner in a process of the physical entity. Figure 8 displays the differences and similarities as well as the main components of a DT.

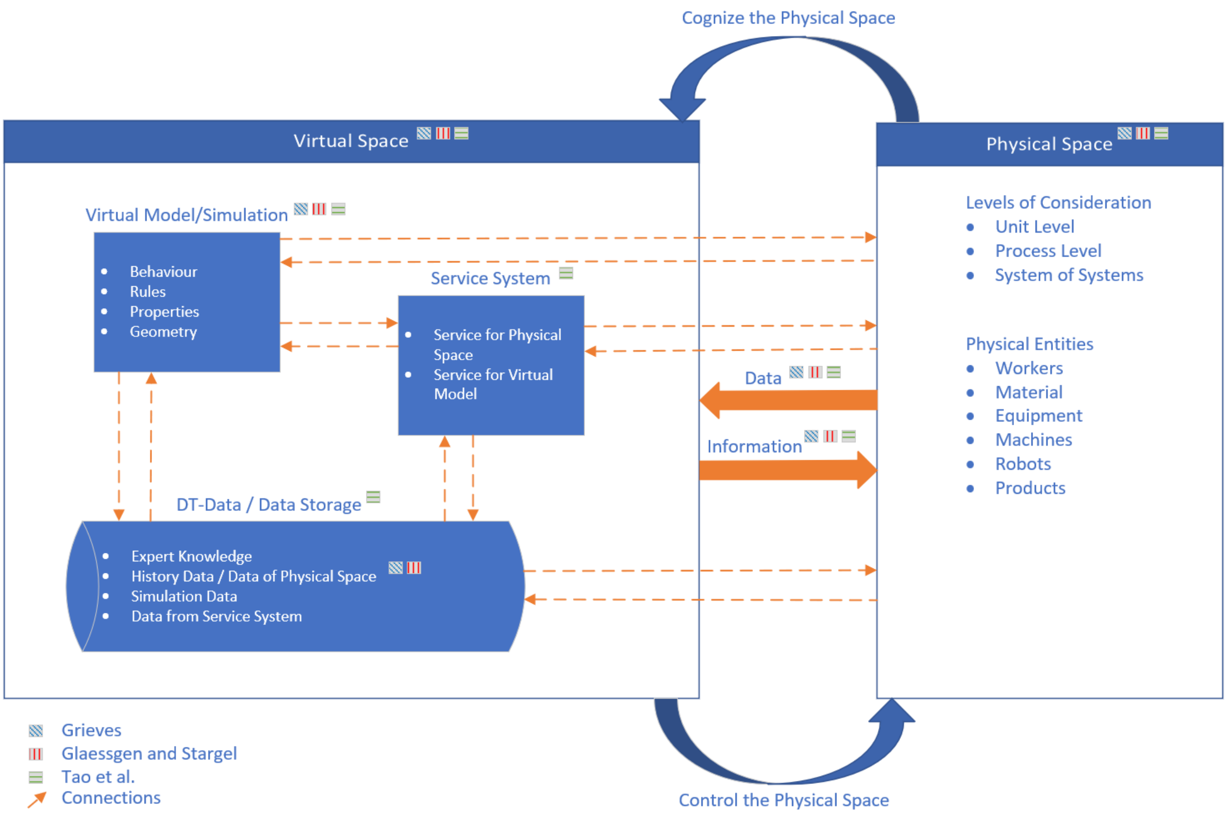

Figure 8. Digital Twin components [10,13,20,49].

3.4. *Systematic Evaluation of the Identified Literature*

After this discussion of the most used definitions and the delimitation of the term DT, the content of the papers is described in more detail. In Table 8, the papers are clustered according to their content into: (1) enablers and implementation concepts, (2) areas of operation and state of development, (3) virtual model creation, (4) enterprise information systems, (5) decentralized applications, and (6) machinery prognostics and maintenance management.

Table 8. Clusters according to the content of the paper.

Cluster	Records	Records [%]
Enablers and Implementation Concepts	5	17.86
Areas of Operation and State of Development	3	10.71
Virtual Model Creation	4	14.29
Enterprise Information Systems	6	21.43
Decentralized Applications	7	25.00
Machinery Prognostics and Maintenance Management	3	10.71

3.4.1. Enabling Concepts

A total of 17.86% of the identified articles were assigned to the cluster “enablers and implementation concepts”. Krajčovič et al. present several steps to transform logistics systems toward logistics 4.0, whereby the development of factory management strategies from reactive to predictive and proactive approaches is described. To enable those strategies, the implementation of DT technologies is suggested [45]. These DTs can be developed and applied for all phases during a product’s life cycle, which can be divided into product design, product manufacturing, and product service. To illustrate the possible usage, different cases are described for the design of bicycles, shaft manufacturing, and power transformer service [13]. For shop-floor processes, on the other hand, different stages toward a DT can be described. In the last stage, the virtual and physical spaces interact and converge. For the manufacturing phase, the interaction between physical entity, VM, and Service System are shown in an activity diagram; the operations are differentiated into before production, during production, and after production. To ensure the convergence between physical and virtual space, the VM must evolve during operation [17]. In addition, Brenner and Hummel demonstrate a new concept for mobile digital shop-floor management at the ESB Logistics Learning Factory. For this concept, an indoor positioning system, a social platform for communication and knowledge transfer between employees, mobile devices, and a large mobile interactive board are used. It is intended to investigate the impact of organizational structure, leadership, and communication of the new concept on efficiency and productivity [48]. Regarding the implementation of DTs, Uhlemann et al. mention the special situation of small and medium-sized enterprises (SMEs), which face more difficulties in implementing a DT for production systems. SMEs are characterized by a low degree of automation and interlinking of their production, as well as insufficient machine and process data acquisition. To overcome these obstacles for logistics processes, a combination of sensor-based tracking and machine vision technologies is suggested and described [29].

3.4.2. Areas of Operation and State of Development

A total of 10.71% of the identified papers were assigned to the cluster "areas of operation and state of development". The results of the literature review on implementation of DTs show discussions in various application areas within the product lifecycle. A total of 50 papers were included, with 38% assigned to prognostics and health management (PHM), 35% to production, 18% to design, and 9% to other areas. In contrast, applications for dispatching optimization and operational control are currently missing from the literature [12]. Kritzinger et al. conducted another literature review, focusing only on production and including and categorizing 43 papers to analyze the production category in more detail: 55% of the publications were concept papers, 26% case studies, 14% reviews, and 5% definitions of DTs. A majority of 49% dealt with production planning and control, 14% with maintenance, 12% with the product lifecycle, 9% with manufacturing in general, 9% with layout planning, and 7% with process design. However, the analysis of the degree of implementation showed that only 2.38% of the case studies met the definition of a DT [11]. Agalianos et al. analyzed 14 papers to DES and DT in the context of warehouse logistics. They further stated that most available DES software solutions are only capable of offline simulation, while a trend to real-time simulation can be seen. Thus, current implementation only includes some of the DT dimensions. A lack of applications of DTs in scientific publications was identified, emphasizing the very early stage of DT development in warehousing. At the same time, a strong potential to solve several problems in warehousing is highlighted when DTs are applied, for example, to routing, scheduling, resource allocation, waste and energy reduction, storage reduction, transport reduction, estimating warehouse employee intentions, optimizing space utilization, KPI presentation, decision support, forecasting, and prediction. Nevertheless, implementation or integration of DTs in this area are missing and the potential remains theoretical [35].

3.4.3. Virtual Model Creation

A total of 14.29% of the identified papers were assigned to the cluster "virtual model creation". As highlighted in the discussion on DT definitions, the VM is an essential part of a DT. To speed up the creation of this model, several frameworks and approaches can be found within the analyzed papers. Coelho et al. conducted a literature review of 41 articles to identify the different activities involved in in-house logistics processes. These can be differentiated between distribution facilities and production facilities. The activities receiving, storing, order-picking, cross-docking, and shipping are identified within distribution facilities. For production facilities, the distribution facility is described as a sub-model of the system. The activities were divided into receiving, storing, order picking, line feeding, and line-side presentation. Real entities were matched with predefined simulation objects to create a simulation model. Human pickers were matched with workers, cobot pickers and transporters were matched with vehicles, storage and product locations with combiners, products as well as bins and orders with entities. To evaluate this framework, two offline simulation models were created and validated [30]. Jiang et al. present several generic building blocks for creating the VM of a DT for discrete manufacturing systems based on DES. It is differentiated between elements and relationships: man, machine, material, method, and environment are described as elements, and the production relationship describes the hierarchical structure whereby the logistics relationship covers the network structure of the system. To verify the concept, it was implemented in a production system for aerospace components. The VM within the DT is mainly used for real-time production monitoring and production schedule verification. It is mentioned that no formal verification and validation of the VM has been performed [32]. Another approach was taken by Sommer et al. to create a partially automated simulation model. First, spatial parameters such as position and geometries are obtained from 3D scanning methods, e.g., photogrammetry or LIDAR scans. The scans are then matched with additional information about the objects from a reference database of computer-aided design models. Further, company-specific information must be added to the simulation model, which is obtained through surveys. Defined parameter groups are enhanced with specific data from material flow planning, investment planning, and capacity planning. Computer-Aided Design (CAD) data and data from the scanning process are transferred via XML directly into the DES environment used. This approach is intended to speed up the generation time of a simulation model. The work focuses on the generation of a virtual offline model, but other dimensions and requirements of a Digital Twin are not addressed [21]. It is shown that the virtual representation of humans plays an important role for DTs of logistics systems. Digital human simulations represent workplaces and humans, as well as interactions between them. Most digital human models include a set of predefined functionalities and capabilities so that humans can be modeled like technical equipment. To mirror humans more accurately in VMs, Nikolakis et al. suggest a different approach. Here, human motions are captured using low-cost optical, force, and torque sensors. Modeling parameters, motions, and constraints of a specific human can be captured and integrated into the simulation. A case study for pick and place processes in a warehouse is presented, where motions and physical characteristics of three operators were recorded. After the record, the simulation designs a desired workspace and assembly steps in terms of ergonomics and cycle motion times [44].

3.4.4. Enterprise Information Systems

A total of 21.43% of the papers were assigned to the cluster "enterprise information systems". To successfully implement a DT, a bidirectional connection to established enterprise information systems is necessary. In general, a digital thread through enterprise information systems is an important part of enabling the use of DT technologies throughout the product lifecycle. Therefore, product lifecycle management (PLM) systems, enterprise resource planning (ERP) systems, manufacturing execution systems (MES), and customer relationship management (CRM) systems should be considered and integrated to cover operational tasks such as production planning, control actions for production and logistics systems, as well as monitoring and dispatching of production processes and equipment [19]. In more detail, Grigoriev et al. describe the required data and their sources for machine-building enterprises. Portfolio information, production program data, as well as important performance indicators can be obtained from advanced planning systems (APS), MES, supervisory control and data acquisition (SCADA) systems, multi database container (MDC), and machine data acquisition (MDA) systems. product data management (PDM), CAD and computer-aided manufacturing (CAM) systems contain information on design and process parameters. These systems can also be accessed for the description of the technological process and the required resources, as well as information on maintenance and repair processes. The availability, reliability, and utilization of technological resources and information of WIP are available through ERP, SCADA, MDC, and/or MDA systems [37]. Other authors propose an MES-centric approach for DT, whereby the MES is connected to the physical system and contains all information the DT needs for its purpose. In addition, the DT is connected to the MES and receives all historical and real-time data required for the mirroring of the operational tasks. A use case for the optimization of the material supply scheduling process within a frame shop production is presented. Thereby, an analytical model is used to predict the impact of different decisions, and the LINGO software is used for optimization. This has improved the line balance rate of the production by 45% compared to the previous planning process as well as significantly reducing the reaction time to errors [41]. Likewise, Agostino et al. present an MES-centric approach, whereby a DES is used as a VM. The model represents a workshop of an automotive supplier. A sequence diagram shows how the communication between MES, optimization algorithm, and DES could proceed in time. In this case, dispatching rules and production schedules should be optimized by using a genetic algorithm. Compared to the previously calculated schedule, the simulation results show potential regarding the number of tardy jobs, throughput time, and monthly working time usage. However, the conclusions are derived from offline simulations only [36]. Nevertheless, to address dynamics on different levels of a production logistics system, the connection with other enterprise information systems is necessary. To dissolve dynamics on various levels, Pan et al. suggest different computer paradigms. The first level of dynamics described occurs at the shop-floor and concerns individual units. These dynamics can be eliminated by rescheduling tasks and resources using edge computing if no other operations are affected. If the production system also suffers from dynamics, it should be solved by fog computing, if no other decision-making subsystem is concerned. When dynamics occur on an enterprise level, it is suggested to solve them by using cloud computing. Thus, the dynamics can be solved by rescheduling resources, adding new resources, and changing customer demands. A synchronization method is suggested to pass the solutions through the different levels of observation. To evaluate their multidisciplinary design optimization method, a simulation model was created by the authors. With this approach, dynamics on different levels could be eliminated. The results outlined potentials regarding production scheduling and warehouse costs and showed that better results can be achieved when dynamics occur in the early stages of the production process [33]. Likewise, Guo et al. describe coupling problems in the optimization of production and logistics. A flexible cellular manufacturing based on a DT is presented to solve these problems. In this case, the optimization objectives are the improvement of the line balance rate, per capita productivity, and the number of operators. For this purpose, the production layout, production scheduling, logistics distribution, and equipment testing are optimized by addressing the coupling problem by a sequential ordering of the separate parts. The concept was implemented in an air conditioner production line and showed that production capacity was improved by 58.3%, WIP by 77.8%, line balance rate by 25.2%, per capita production capacity by 29.8%, and the number of operators by 28.3% [31].

3.4.5. Decentralized Applications

A total of 25.00% of the identified papers were assigned to the cluster “decentralized applications”. In this context, a trend toward decentralized applications and the use of CPS can be observed in production and logistics [3]. Due to decentralized decisions, the simulation of these systems becomes more difficult. Some authors address this problem by integrating the control mechanism of these entities in their simulations. Herakovic et al. propose a holistic structure to create a DT for manufacturing processes. Each entity is represented by a holon to enable holarchic (distributed) control. To represent each holon in the VM, an agent-based simulation (ABS) is used, where each holon is an agent. A case study is conducted in a laboratory environment including a conveyor belt, cobots, and seven workstations. With a predefined logic, the DT controls the different holons via the

ABS considering real-time information from the physical entities. It is stated that the DT can make predictions and control the production line, considering malfunctions of the holons [43]. AGVs are increasingly finding their way into the industry to enable flexible material supply within the production system. Existing fleet management systems for AGVs are mainly focused on routing and localization, without considering the real-time information on manufacturing processes. Therefore, Yao et al. combine the AGV simulator with a DES to create a VM for a DT. To evaluate this method, a case study was conducted in a laboratory environment, including weight scales at workstations and AGVs. With an OPC UA interface, the physical entities communicate with the VM and the service system. Information about the progress of work at the workstations is derived from the weight scale data. The controlling mechanism of the material supply is also predefined [46]. In addition to this, Bottani et al. address this problem by integrating the operational software code of the AGV into the DES of the production system. In a simulation study, a traditional pre-planning policy is compared with two different optimization policies (min. production time, min. logistics time) of the DT. In addition, three different scenarios are investigated in terms of selling price and demand variation. The simulation results show that different strategies could handle different scenarios better than others. It is suggested that DT should change its strategies depending on the current situation of a manufacturing system [47]. Another paper deals with the integration of RTLS information as well as with the integration of control mechanisms and other information on AGVs and cobots in a DT. The concept is tested in a laboratory environment and the game engine Unity is used as a virtual environment to create the VM. Applications for workstation design by using IMMA (Intelligent Moving Manikins), for picking processes, routing, education, and monitoring are described; service systems need to be implemented and more experiments are necessary to evaluate the potential benefits of this approach [38]. Nevertheless, predefined control mechanisms can lead to suboptimal results, and, in the case of material flow systems, long waiting times and wasted energy may be the result. To tackle this problem, Wang et al. designed a proactive material handling system based on DT. The concept focuses on discrete manufacturing shop-floor systems and was exemplarily implemented into tire mold production. A time-weighted multiple linear regression model is used to predict the energy consumption and travel distance for the current situation. Therefore, different real-time information from various sources is considered. An NSGA 2 algorithm (a multi-objective genetic algorithm) is used to optimize these parameters and, in comparison to the legacy passive material handling system with predefined control mechanisms, leads to a 52.7% and 66.7% reduction in energy usage and travel distance, respectively [42]. Vachalek et al. also optimize energy consumption and reduce waiting times but shorten production time by using DTs. A miniature physical model of a production line with three hardware boards as workstations, a conveyor belt for transport, and optical sensors for color detection, was created. At this stage, it has been demonstrated that the VM accurately reflects the physical unit. The DT in this work is limited to presenting a concept for linking the physical entity and VMs, and, thus, no optimizations are presented [34]. A DT for the final stage of a truck assembly line also shows a successful linkage between the physical entity and the VM. The assembly process is performed by eight workstations on the main conveyor belt. Every second, the state (“works”, “awaiting components”, “waiting for a frame”, “blocked”) of the workstations are updated. The model enables near-real-time monitoring of the physical system and potential detection of problems within the system before they occur. If problems are detected, the model will report and provide information about them. Nevertheless, no optimization within the DT and no closed-loop control are realized [40]. Moreover, in the included publications, application programming interfaces (APIs) and database approaches [36,41] as well as OPC UA [22,46] are described as methods for linking physical and virtual space. Furthermore, ISO also proposes the use of MTConnect for physical entities in production systems in its draft Digital Twin framework for manufacturing. For IoT devices various protocols such as OCF, LwM2M, oneM2M, and OPC-UA are proposed.

MQTT is mentioned as well, as it supports the "publish" method in the transaction protocol. The layer two protocol TSN is also referred to for the transmission of time-critical data [50].

3.4.6. Machinery Prognostics and Maintenance Management

A total of 10.71% of the identified papers were assigned to the cluster "machinery prognostics and maintenance management". The identified papers in this cluster are more focused on the machine health management and investigate measures to enable predictive maintenance and forecast the remaining lifespan of machine parts. To increase the utilization rate of key machines, a DT for a manufacturing company in the electronics industry is developed by Hu et al. The DT incorporates various data in real-time, such as the number of finished goods, down- and working time, vibration, temperature, information of suction nozzles and feeders, and force measurement data of surface mounting machines. It is used for predicting machine failures and, thus, for predictive maintenance as well as for changing parameter settings of the machines. Due to the application focus, it is difficult to adopt this approach to other products and production systems [39]. Zheng et al. establish a DT for a welding production line. To enable synchronous simulation, an OPC UA server for communication via the internet, and a socket server for communication via local area networks are used. The physical entity could mirror the system with a maximum delay of 1 s. Real-time visual monitoring of the production process is realized to ensure the operational efficiency of the equipment and provide information about the welding quality [22]. A case study of wind turbines also shows the potential of DT for PHM processes. The traditional fault cause prediction based on vibration signals (P-Method) is compared with the DT approach and it is shown that the prediction of tooth wear could be improved by 17%, tooth fatigue by 30%, and tooth breakage by 20% [27].

3.5. Case Study Analyses

The analyzed papers describe different concepts and approaches to speed up the creation of the VM, connections to different enterprise information systems, successful linkages to and implementation of the DT, as well as the varied potential of this technology. Nevertheless, different implementation levels of the described DT for production logistics processes were found. To gain further insights into the state of the art, papers reporting case studies (20 papers) are analyzed in more detail. As displayed in Figure 5, the five dimensions of Tao et al. are most often used in the studies found to define a DT. Therefore, the authors also apply these dimensions to evaluate the degree of coverage of the characteristics of a DT in the presented case studies in Table 9.

The distribution of the fulfillment rate can be seen in Figure 9. A majority of 18 papers (90%) present a VM of a real physical system or entity. DT data were considered by 14 papers (70%). A service system is implemented by twelve papers (60%) and a connection between the other dimensions was created by seven (35%) papers. These seven papers (35%) consequently implemented all five dimensions, with two of them (10%) created for laboratory environments, while three other papers (15%) deal with PHM, which is not consistent with the core logistics tasks.

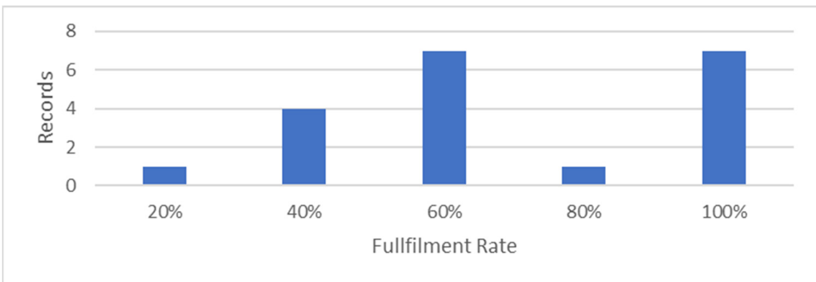

Figure 9. Distribution of fulfillment rate.

Table 9. Fulfillment of five dimensions of Digital Twins.

Ref. No.	Authors and Year	Five Dimensions of Tao et al.					Fulfillment
		Physical Entity	Virtual Model	DT Data	Service System	Connection	
[30]	Ceolho et al. 2021	x	x				40%
[31]	Guo et al. 2021	x	x	x	x		80%
[32]	Jiang et al. 2021	x	x	x			60%
[33]	Pan et al. 2021		x		x		40%
[34]	Vachalek et al. 2021	x (lab)	x	x			60%
[36]	Agostino et al. 2020	x	x		x		60%
[38]	Hauge et al. 2020	x (lab)	x	x			60%
[39]	Hu et al. 2020	x	x	x	x	x	100%
[40]	Makarova et al. 2020	x	x	x			60%
[21]	Sommer et al. 2020	x	x				40%
[41]	Wang and Wu, 2020	x	x	x	x	x	100%
[42]	Wang et al. 2020	x	x	x	x	x	100%
[43]	Herakovic et al. 2019	x (lab)	x	x	x	x	100%
[44]	Nikolakis et al. 2019	x	x	x			60%
[22]	Zheng et al. 2019	x	x	x	x	x	100%
[45]	Krajcovic et al. 2018	x					20%
[27]	Tao et al. 2018	x	x	x	x	x	100%
[46]	Yao et al. 2018	x (lab)	x	x	x	x	100%
[47]	Bottani et al. 2017		x		x		40%
[48]	Brenner and Hummel, 2017	x (lab)		x	x		60%
	Allocation	90%	90%	70%	60%	35%	

Also, different VMs were presented to mirror the physical entity. The decision on which model should be implemented depends on various factors. Also, a multitude of modeling technologies (e.g., discrete event simulation, physical simulation, automated guided vehicle simulation, agent-based simulation) were found by systematically analyzing the resulting research records. Table 10 summarizes the identified modeling technologies for production logistics processes.

Table 10. Virtual Models for Digital Twins.

Abbr.	Name	Records	Records [%]
DES	Discrete Event Simulation	9	45.00
PS	Physical Simulation	3	15.00
AGV Simulator	Automated Guided Vehicle Simulation	2	10.00
ABS	Agent-based Simulation	1	5.00
AM	Analytical Model	1	5.00
CRS	Catmull-Rom Spline	1	5.00
GE	Game Engine	1	5.00
KD	Knowledge Database	1	5.00
MDO	Multidisciplinary Design Optimization	1	5.00
TWMLR	Time-Weighted Multiple Linear Regression	1	5.00

In general, DES is the most used simulation technique for production and logistics systems [51]. This is consistent with the results of this analysis, showing that DES is also most often used to create a VM in the context of DT for production logistics processes (nine papers). Two papers propose a combination of DES and AGV simulators to integrate the control mechanism of the AGV. An increasing trend toward such hybrid simulation approaches can be observed regarding simulations in the context of Industry 4.0 [52]. Regarding PHM, three papers use physical simulations. Several other approaches were identified, but their application is indicated to be quite low because each of them was only referenced once. In the analyzed papers, various objectives were pursued to tackle different problems. To give an overview of possible potentials for logistics processes, Table 11 shows the objectives addressed by the presented studies. In general, the purpose of a VM is to represent the behaviors and functions of the real system virtually in an executable model. Hence, this objective is not explicitly stated.

Table 11. Targeted objectives.

Objective	Records	Records [%]
monitoring	5	25.00
production scheduling	3	15.00
AGV control	3	15.00
overall equipment effectiveness (OEE)	3	15.00
line balance rate	2	10.00
reaction time	2	10.00
workstation design	2	10.00
lead time	2	10.00
per capita productivity	1	5.00
number of operators	1	5.00
warehouse costs	1	5.00
energy consumption	1	5.00
travel distance	1	5.00
travel time	1	5.00
shop-floor management	1	5.00

Production system machine monitoring, production scheduling, AGV control, as well as overall equipment effectiveness (OEE) were most often addressed as the main objective of the identified DTs studies. Although no paper mentioned OEE per se, many studies address this performance indicator by considering the underlying OEE indicators, namely, quality rate, machine availability, and machine performance. The line balance rate, reaction time, workstation design, and lead time are also addressed in two papers each. Several other objectives have been tackled by individuals. As displayed in Table 12, the DTs were also developed for different areas of application. Four of the papers do not describe their application domain and are, therefore, not assignable (20%).

Table 12. Application areas.

Domain	Records	Records [%]
laboratory production	5	25.00
not assignable	4	20.00
automotive	3	15.00
electronics	2	10.00
metalworking	2	10.00
distribution center	1	5.00
aerospace	1	5.00
warehouse	1	5.00
energy	1	5.00
others	1	5.00

Furthermore, it can be observed that most of the DTs were investigated in laboratory environments (25%). In addition, investigations were carried out in the automotive industry (15%), in the electronics industry (10%), in the metalworking industry (10%), in the aerospace industry (5%), and in the energy sector (5%), as well as in warehouse (5%) and distribution center (5%) environments.

4. Discussion

Although different definitions of DT can be found in the analyzed literature, commonly used definitions can be identified. A comparison between these shows that the levels of detail, as well as the focus area, differ, but the basic concept remains the same. In comparison with Grieves, Tao et al. added two dimensions and described the dimensions in more detail. This is also the most often used definition within the analyzed literature.

Therefore, the level of implementation of the found case studies is also evaluated on this basis. It turns out that only four papers present a fully implemented DT for the core activities of logistics [41–43,46]. Two of these papers show implementation in laboratory environments, leaving two industrial applications. In general, most case studies can be assigned to laboratory production lines, followed by applications in the automotive, electronic, and metalworking industries. Besides the different levels of implementation, different approaches for the creation of a VM can also be observed. For production logistics processes, DES is most often used, as it is also the state-of-the-art for simulating production logistics systems. Some authors present predefined building blocks and standardized processes to speed up the creation of DES models. However, most available DES software solutions still lack real-time capabilities [35], which are an essential part of DT technology. For the identified PHM processes, physical simulations are used. Some hybrid simulation approaches can also be found to integrate control mechanisms of decentralized applications. To successfully integrate a DT, a connection to enterprise information systems, as well as to sensors and actuators must be established. Different information systems can be found in various configurations in companies. The connection between and consistency of data in these systems can also vary widely. Another difference in the analyzed DTs is their main objective. Consequently, different requirements must be met, and individual consideration must be given to the information systems to which a bidirectional connection must be established. It is also conceivable that DT technologies will become an inherent part of enterprise information systems or manufacturing execution systems.

To highlight the contribution of this literature analysis, a comparison is made with existing literature reviews related to DT. Kritzinger et al. analyzed papers regarding DT in the manufacturing area. In this context, a DT was described as consisting of a digital shadow, a digital model, and a bidirectional link between these two elements. Based on this description, the level of integration of the analyzed literature was evaluated. A focus area and the core technologies of these papers are also described [11]. Stark and Damerau analyzed 19 different definitions of DT. Based on this, they defined a DT with three components: a digital master, a digital shadow, and a linking mechanism. In addition, the scope and type of a DT are divided into eight dimensions, with each dimension having three to four levels. The dimensions include integration breadth, connectivity mode, update frequency, CPS intelligence, simulation capabilities, digital model richness, human interaction, and product life cycle [14]. Tao et al. analyzed 50 papers, eight patents, and six best practices of leading companies. This review is focused on industrial DT applications in general; thus, current developments of DT in the industry, as well as DT applications, are described. The literature was assigned to the application areas of design, production, PHM, and others, showing that PHM is the most popular application area for DT. The importance of DT modeling is highlighted, as well as the fact that no consensus can be found in how to build a DT model. The authors conclude that cyber-physical fusion is one of the major challenges of DT and a lack of universal frameworks is identified [12]. Researching a different application area, the literature review of Agilianos et al. is focused on DT for warehouse processes, stating that the development of DT in this area is still at the initial stage and that DES models must be enhanced with real-time functionalities [35]. This paper complements the previous reviews on DTs by adding non-investigated aspects focusing on production logistic processes. First, the most used definitions of DTs in this application area are analyzed and discussed, highlighting similarities and differences between these definitions. As a result, the main components and important functionalities of a DT have been pointed out. In addition to mentioned concepts and reviews, 20 case studies are analyzed in more detail in a second step and evaluated based on the five dimensions of Tao et al. Due to the integral role of the VM in a DT, the approaches and technologies used to create a VM are analyzed and discussed. Together with the analysis of the pursued optimization goals, this provides a starting point for new developments based on already existing approaches and an overview of the potential benefits in this area. The literature analyzed reveals some research gaps and future research directions. It has been shown that there are different approaches for the implementation of a DT for production logistics. Therefore, different requirements must be met as well. These requirements for a DT implementation have not been systematically surveyed and addressed so far. All the literature analyzed deals with discrete production systems, without addressing logistics challenges in the process industry. Despite the description of various information sources, no data models could be found that would allow the DT to be independently connected via APIs. As described, much of the analyzed literature deals with the creation of VMs. Thus, the real-time capabilities and the connection with the physical entity as well as the service system are often neglected. This should be considered in more detail in future research. Overall, only a few fully implemented DTs in industrial environments for production logistics processes could be found. To comprehensively determine the potential benefits in real-world applications in this area, further fully implemented DTs in industrial environments need to be investigated. Although the use of DTs within the design phase is discussed, virtual commissioning with DT technologies is not addressed at all. This is supported by a review by Lechler et al., focusing on virtual commissioning and showing no hits for application in logistics processes [53]. Due to the close relationship between DT and CPS concepts, in future literature reviews, this term should be included to extend the search.

5. Conclusions

Based on a systematic literature review focusing on implementation and on implementation concepts of DTs in production logistics, this paper shows current developments and approaches to DTs in this area. The current state of research on DTs for production logistics processes is highlighted and discussed. Basic concepts, other reviews as well as implementation approaches are analyzed. An overview of the most common definitions of DTs in this field is given and commonalities and differences in the understanding of DT are presented as a basis for further discussion. Detailed analyses of reviewed case studies show possible application areas as well as objectives addressed by the different DT implementation approaches. The technologies used for the creation of the VM are also considered. Research gaps and possible future research directions in this area are also identified and discussed. In sum, it must be stated that investigations regarding the application of Digital Twins in production logistics are still in an early stage of development and profound industrial applications are still missing. This can be seen as motivation for future research initiatives which aim to combine theory-based explorations of logistics systems with a set of empirical research methods.

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