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Review

Production logistics digital twins: Research profiling, application, challenges and opportunities

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ABSTRACT

In the era of Industry 4.0, Production Logistic Digital Twins (PLDTs) have garnered remarkable attention from both academic and industrial communities. This is evident from the growing number of research publications on PLDTs in international scientific journals and conferences. However, given the diversity and complexity of production logistics activities, there is a pressing need for systematic literature review to chart past research and identify potential directions for future endeavors. Therefore, this study primarily focuses on the application of Digital Twins (DTs) in Production Logistics (PL). Firstly, an analysis of PLDTs research profiling is carried out based on general trends, keywords, application scenarios, and basic functions. Secondly, the functional characteristics of PLDTs are examined while summarizing their advantages and limitations across various application scenarios such as transportation, packaging, warehousing, material distribution, and information processing. And the roles played by smart technologies such as Internet of Things (IoT) in PLDTs system are discussed. Finally, possible challenges and future directions of PLDTs in industrial application are presented, accompanied by appropriate classification and extensive recommendations.

1. Introduction

Manufacturing enterprises are experiencing subtle changes under the impact of Industry 4.0, particularly in the field of Production Logistics (PL). PL is committed to the direction of automation, digitalization and wisdom with thinking, perception, learning, reasoning and autonomous decision-making capabilities [1]. As an essential link between shop-floor supply and production processes, PL accounts for approximately 95% of the entire production life cycle [2]. This shows that effective and reasonable PL management plays a momentous role in augmenting the competitiveness and economic efficacy of enterprises, especially for the intelligent development and digital transformation of today's enterprises.

The initial focus of the PL management approach was on scientifically planning, allocating, and controlling material flow within production processes. However, with the emergence of Industry 4.0, the emphasis of PL management has shifted towards information flow management, resulting in an increased demand for flexibility, agility, and consistency of real and virtual interactions in the Production Logistics System (PLS) [3]. This poses various challenges for researchers and practitioners alike. For instance, (i) how to effectively connect the virtual and physical worlds while realizing seamless integration and

Abbreviations: PLDTs, Production Logistic Digital Twins; DTs, Digital Twins; PL, Production Logistics; IoT, Internet of Things; PLS, Production Logistics System; LDT, Logistics Digital Twin; PLAs, Production Logistics Activities; CC, Cloud Computing; CPS, Cyber-Physical Systems; AGV, Automated Guided Vehicle; AR, Augmented Reality; AMR, Autonomous Mobile Robot; ST, Simulation Technology; MR, Mixed Reality; IIoT, Industrial Internet of Things; PLE, Production Logistics Equipment; DES, Discrete Event Simulation; VR, Virtual Reality; RFID, Radio Frequency Identification; ML, Machine Learning; AI, Artificial Intelligence; RL, Reinforcement Learning; DL, Deep learning.

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real-time interaction in the complex technical landscape [1]. (ii) How to systematically integrate heterogeneous systems and aggregated data platforms under big data environments characterized by massive volume and heterogeneity [4]. And (iii) how to optimally utilize economical computational resources to accomplish the most precise synchronous control of PL in complex environments featuring varying levels of dynamic disturbances [5].

Aligned with Industry 4.0, the concept of Digital Twins (DTs) has been extensively employed in manufacturing research since its inception. DTs is aimed at representing and optimizing physical objects through virtual models driven by a combination of data and models. Recently, the terms Logistics Digital Twin (LDT) and PLDTs have appeared in many works, with the goal of improving the performance of logistics. For example, Piancastelli et al. [6] derived the architecture of LDT and pointed out that LDT helps management to make decisions, evaluate and reduce the risk of Production Logistics Activities (PLAs) scenarios, etc. Thürer et al. [7] proposed a new architecture for PLDTs. Kaiblinger et al. [1] summarized the common definitions of DTs in the field of PL. More studies have discussed that DTs brings new concepts, models and ideas to the intelligent operation of logistics with its characteristics of virtual simulation, evaluation, prediction and autonomous decision-making [8]. It is also shown that DTs is an effective way to realize the integration, interaction and intelligent interconnection of production and logistics processes in the virtual world and the physical world [4].

In recent years, there has been a proliferation of reviews exploring PLDTs, with each offering unique insights. (i) In terms of research interests, Pawlewski et al. [8] described the research implications of using DTs to optimize intralogistics processes and named it Digital Twin Lean Intralogistics. The research results have indicated a growing interest in the terms “digital twins” and “intralogistics”. (ii) As to the virtualization integration of PLS, Fottner et al. [9] discussed recent research advances in autonomous systems in intralogistics. And the importance of DTs, modeling and simulation techniques for the virtualization of the entire intralogistics system was emphasized. Kosacka-Olejnik et al. [10] addressed the question of how the DTs concept can support internal transport systems. Explained that DTs supports internal transport systems by establishing dynamic links and correspondences with real objects and internal transport processes. (iii) As for the application scope of DTs, Zafarzadeh et al. [11] classified PLAs into 3 categories. The share of 10 groups of enabling technologies in PLs, such as DTs, was systematically reviewed and evaluated. It was also shown that there are applications of DTs in PLAs such as tracking and location, material distribution and warehousing. Most recently, Kaiblinger et al. [1] discussed the common definitions, features and functions of DTs in the field of PL. The current state of development and implications of the latest implementations were outlined, and 20 application cases were evaluated to identify current research gaps.

As previously mentioned, researchers have emphasized the role of DTs as a crucial factor for virtualizing PL processes in their analysis of PLDTs. This is consistent with the urgent need for information-physical fusion technology during the digital transformation of today’s manufacturing industry. To further describe the role of DTs in specific PLAs, this study focuses on the latest applications of DTs in PL and supplements the discussion of common application scenarios, methods or theories, and related intelligent technologies of existing PLDTs from the perspective of functional characteristics. Firstly, the common application scenarios of DTs in PL are discussed based on keyword analysis, including transportation, packaging, warehousing, material distribution and information processing. And the distribution of decision support, simulation, planning, monitoring, evaluation, tracking and positioning, predication and design in each logistics scenario are analyzed. Then, more detailed analysis of the methodologies, functions, and application validation methods of DTs in specific PL activities are analyzed. The roles played by intelligent technologies such as Internet of Things (IoT), big data, and Cloud Computing (CC) in PLDTs system are summarized and discussed. Secondly, the application advantages and challenges of DTs in PL are discussed. Finally, the possible future directions of PLDTs are described from the perspective of industrial applications. This study is a complement to the above research work, providing an appropriate classification method for existing theoretical studies and industrial applications of PLDTs.

The remainder of the paper is structured as follows: Section 2 describes the research profiling of PLDTs. Section 3 provides a detailed analysis of the role of DTs in PLAs. Section 4 describes the role that intelligent technologies play in PLDTs system. The advantages and challenges of existing research methods are summarized in Section 5. Furthermore, Section 6 describes the possible future directions of PLDTs in industrial applications. Finally, to conclude this paper.

2. Research profiling of PLDTs

2.1. Definition

To date, research in the field of LDT has covered several branches of logistics, including PL [10], general logistics [12], e-logistics [13,14], cold chain logistics [15,16] and military logistics [17], etc. The application of DTs within each logistics branch reflects a slightly different focus, as outlined in Fig. 1, which provides an overview of LDT research within each branch of logistics.

PL, also referred to as shop-floor logistics or plant logistics. Based on logistics scope analysis, the boundary of PL within a manufacturing company’s production system commences at the point of raw material input and concludes at the storage facility for finished goods. Thus, PL can be roughly divided into three parts, including material distribution, work-in-process transportation and finished goods warehousing. It is evident that PL plays an integral role in the entire production process and serves as a key component of the intralogistics system’s operation.

In recent times, researchers have shown increased interest in optimizing PL processes using DTs, given the significant advancements in DTs within the manufacturing field. As the most fundamental and critical theoretical system to realize Cyber Physical Logistics System (CPLS) [18], DTs have been extensively applied to tackle PL problems through the integration of cyber-physical fusion [1], data integration [19], and virtual-real co-control [20].

2.2. Methodology

To obtain the most current research outcomes, this paper employs the period spanning 2017 to 2022 as the timeframe for analysis. Keyword search methodology was utilized to explore and sift through the Scopus and Web of Science databases, respectively. The initial keyword combinations used for the search were “digital twin* AND logistics” or “digital twin* AND production logistics” or “digital twin* AND production and logistics” or “digital twin* AND internal logistics” or “digital twin* AND intralogistics” or “digital twin* AND shop-floor logistics” or “digital twin* AND shop-floor logistics” or “digital twin* AND factory logistics”.

To expand the scope of the search, a combination of the keywords “internal logistics” or “intralogistics” was included. It is crucial to acknowledge that the scope of intralogistics encompasses the input stage of the intralogistics system (i.e. supply logistics), the transformation process within intralogistics (i.e. production logistics), as well as the output stage of intralogistics (i.e. sales logistics). Hence, PL is a key component of intralogistics. To narrow down the results, the data obtained was sorted and classified based on the categories tabulated in Table 1. Subsequently, literature relating to the input or output stage of intralogistics was eliminated, while literature pertinent to PL was retained. Ultimately, a total of 132 papers were retained and analyzed.

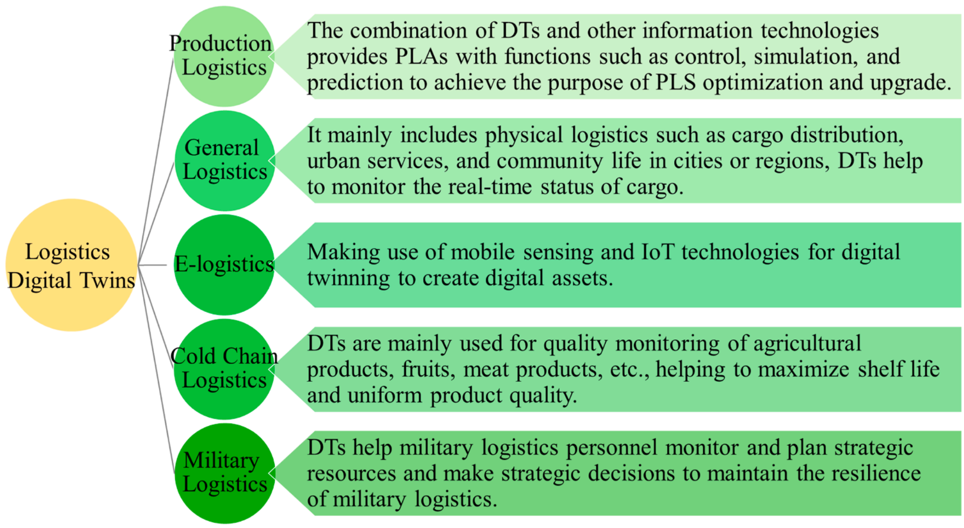

Fig. 1. Research interests in LDT.

Table 1
Inclusion and exclusion criteria.

	Inclusions	Exclusions
Document Type	Journal literature, conference papers	Patents, graduate theses, books, letters
Logistics type	Production logistics or shop-floor logistics or factory logistics or internal logistics or intralogistics	Intra-company supply logistics and sales logistics
The way of writing digital twins	Digital twin or digital twins or DTs or DT or digital shadow	——

2.3. Results analysis

2.3.1. Overall research trends

The bibliometric analysis of the 132 retained publications was executed, and the publication distribution during the 2017–2022 period is depicted in Fig. 2. Among these, conference papers constituted 43.18%, while journal papers accounted for 56.82%, indicating a steady upward trend. These observations underscore the heightened research interest in DTs applications within the PL domain [10]. The distinct variation in the percentage of journal and conference papers also highlights the vital role of DTs and associated solutions in production and logistics, particularly in light of the COVID-19 outbreak [21,22]. It is expected that the number of publications related to PLDTs will continue to show a rapid growth in the coming years.

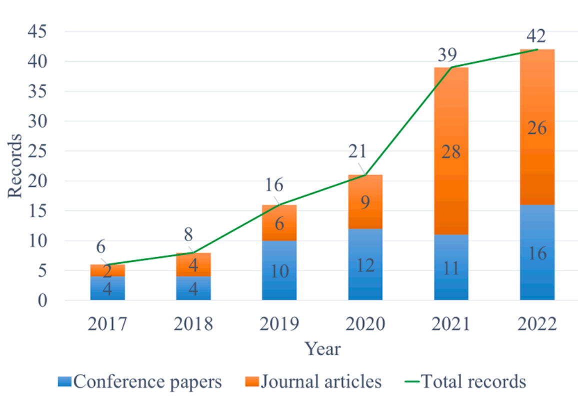

Fig. 2. Publication-distribution per year during the period of the study (132 papers: 2017–2022).

Further insights into how research is distributed among journals and conferences are presented in Fig. 3. Conference papers primarily originated from publishers such as Springer, Elsevier, and IEEE, while journal papers were more broadly sourced and distributed. The figure indicates that not only has the number of PLDTs-related journal articles increased, but the number of journals dedicated to this field has also grown. Although the number of conference papers has not decreased, it also indicates that the concept of PLDTs is relatively new, and researchers have great interest in studying and applying DTs in the PL field.

2.3.2. Subject area analysis

Within this section, the authors elucidate the most relevant subject areas for the application of DTs in the domain of PL. The top three subject areas related to applied research on PLDTs are Computer Science (55.3% of listed publications), Engineering (covering almost 18.18%) and Business, Management and Accounting (covering almost 12.12%).

Among the subject areas listed in Fig. 4, there are also publications assigned to other subject areas, such as Energy, Biochemistry, Genetics and Molecular Biology, Chemical Engineering, Materials Science, Physics and Astronomy and Decision Science. Hence, research and applications pertaining to PLDTs manifest across diverse subject areas and contexts. For example, the automated transportation and management of PL resources appears in disciplines such as Chemical Engineering, Materials Science, Environmental Science and Social Sciences. Although the above-mentioned subject areas represent only a small percentage of all these publications, it is further known that the application of DTs in PL has received attention from different scientific disciplines. Based on the above mentioned, it indicates that PLDTs has received varying degrees of attention and applications across a broad spectrum of disciplines, potentially attributed to the technological advancements in many related fields. Similar conclusion has also been drawn in [10].

2.3.3. Keywords analysis

To further explicate the distinct application scenarios and functions of DTs in PL, this study analyzes the distribution of keywords within the sample, as depicted in Fig. 5. Despite being used less frequently as keywords, “production logistics”, “workshop logistics”, “intralogistics”, and “internal logistics” are overshadowed by the crucial importance of “digital twin/digital twins” and “logistics”, hence demonstrating the indispensability of DTs in modern-day logistics [8]. Meanwhile, the roles played by DTs in PL can be initially determined based on the keywords such as “simulation”, “management”, “optimization”, “analysis”, “decision making/decision support”, “design”, “monitoring” and “prediction”, etc. Furthermore, it is also possible to get a preliminary understanding of the

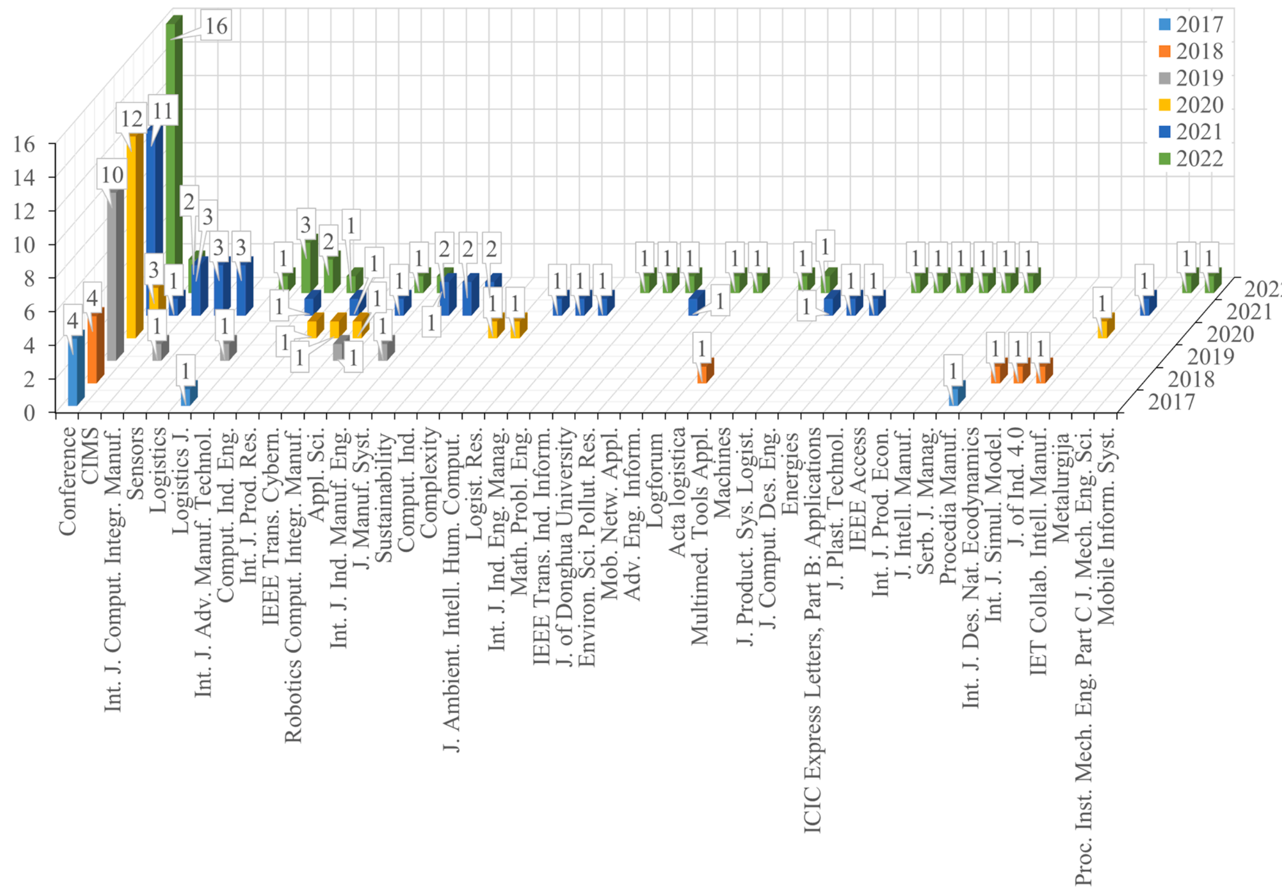

Fig. 3. Publication-distribution of journals during the study period(132 papers: 2017–2022).

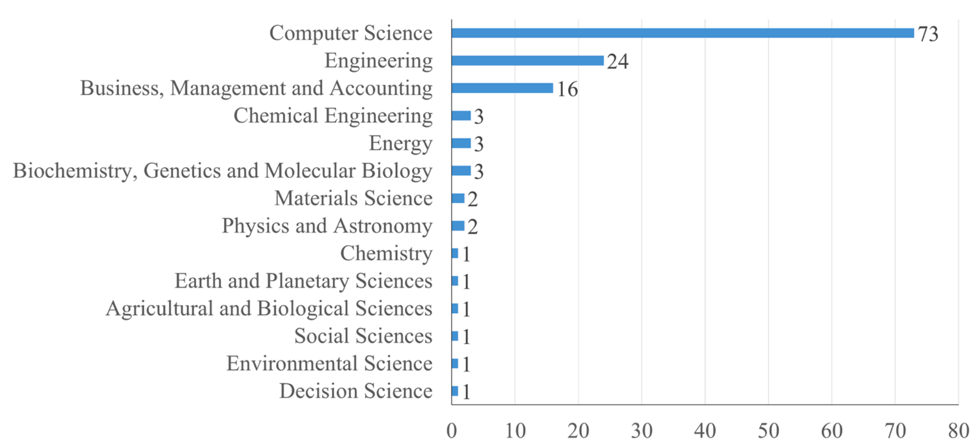

Fig. 4. Number of publications on the DTs applied in production logistic according to subject area (132 papers: 2017–2022).

specific application scenarios of DTs in PL through keywords, such as "material* handling/material distribution/material flow", "schedule/scheduling/distribution/distributed", "AGV/AMR/robot*/co-bots/hybrid automata/multi-agent", "indoor localization/real-time location/tracking/traceability" and "warehouse/warehousing/digital storage/automated warehouse". Based on the above analysis, it becomes clear that DTs play different functions in different PLAs, and the more detailed analysis can be obtained in Section 3.

2.3.4. Application scenarios

To provide a more detailed understanding of the particular application scenarios of DTs in the PL process, and in combination with keyword analysis, the utilization of DTs in PL has been categorized into five distinct scenarios from the perspectives of both material flow and information flow. These scenarios encompass transportation, packaging, warehousing, material distribution, and information processing.

1. Transportation: Logistics transportation is the process of transporting materials (raw materials, auxiliary materials, work-in-progress, etc.) from one production stage to another using logistics facilities (AGV, AMR, RCL, etc.). It is the most important economic activity in the PLS [10].
2. Packaging: Packaging is to protect the product during production, facilitate storage and transportation, and is an important part of the PL process [23].

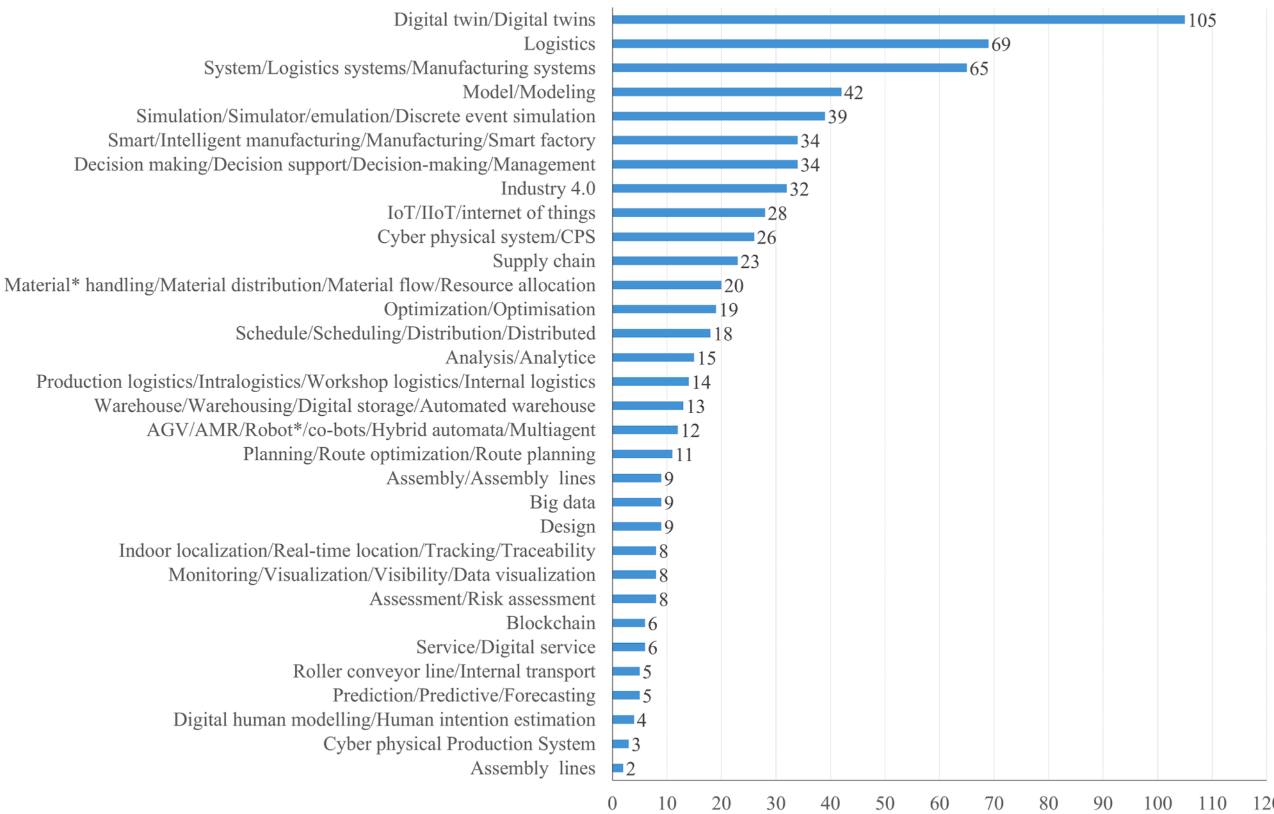

Fig. 5. Frequency statistics of keywords in publications (132 papers: 2017–2022).

3. Warehousing: As the node of PL, warehousing mainly exists in the form of storage warehouses and articulated warehouses, and contains activities such as controlling, classifying and managing inventory [23,24].
4. Material distribution: Material distribution is the process of rational planning and scheduling of raw materials, auxiliary materials, work-in-progress, etc. [25].
5. Information processing: Collecting and processing dynamic information on production processes, logistics facilities, and costs to make forecasts, plans, and decisions related to PL, so that PLAs can proceed more efficiently and smoothly [26].

As illustrated in Fig. 6, it comes as no surprise that information processing related to the management of production and logistics information flow accounts for 29% of the total percentage, driven by the ongoing digital transformation of enterprises. Material distribution activities, such as resource allocation, location, and tracking, account for approximately 24% of the total percentage. Warehousing (20%) mainly includes the process of inbound, inbound management and outbound, especially in the process of joint operation with packing (3%), the phenomenon of inbound stacking is easy to occur. Consequently, DTs in warehousing and packaging activities, as well as in the joint optimization of both, have been studied and applied. Transportation (19%) is a crucial activity that spans all aspects of PL, and has received significant attention from researchers in terms of real-time monitoring, route planning, and synchronous decision-making during transportation. Additionally, ergonomic assessment and safety management for on-site logistics workers have also received attention from researchers.

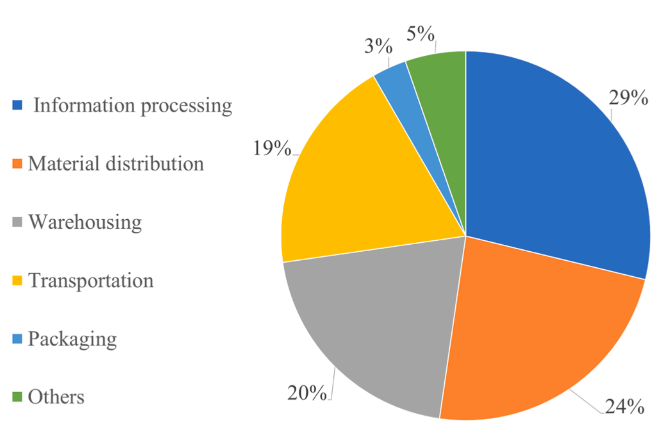

Fig. 6. Distribution of applications of DTs in PLAs (132 papers: 2017–2022).

2.3.5. Function distribution

To comprehensively expound on the vital roles that DTs play in diverse PL scenarios, and building upon the results of keyword analysis and application scenario classification, this section categorizes the functions performed by DTs in information processing, material distribution, warehousing, transportation, and packaging. These functions include decision support, simulation, planning, monitoring, evaluation, design, prediction, and tracking/positioning. The distribution of each function in each scenario is shown in Fig. 7.

As depicted in Fig. 7, the most ubiquitous function employed in PL scenarios is "decision support", particularly in relation to information processing. This observation aligns with the prevailing notion that DTs typically serve as decision support tools in the context of PLAs, as indicated by references [27–29]. Furthermore, utilizing DTs enables activities like PLS design, warehouse planning, and material transportation planning to be simulated within a virtual environment. This iterative simulation process does not require factoring in trial and error costs [30]. Compared to traditional two-dimensional monitoring, DTs provide the benefit of three-dimensional visualization that allows for "real-time monitoring" [31]. Therefore, DTs is widely used in various logistics scenarios. Notably, the "evaluation", "prediction" and

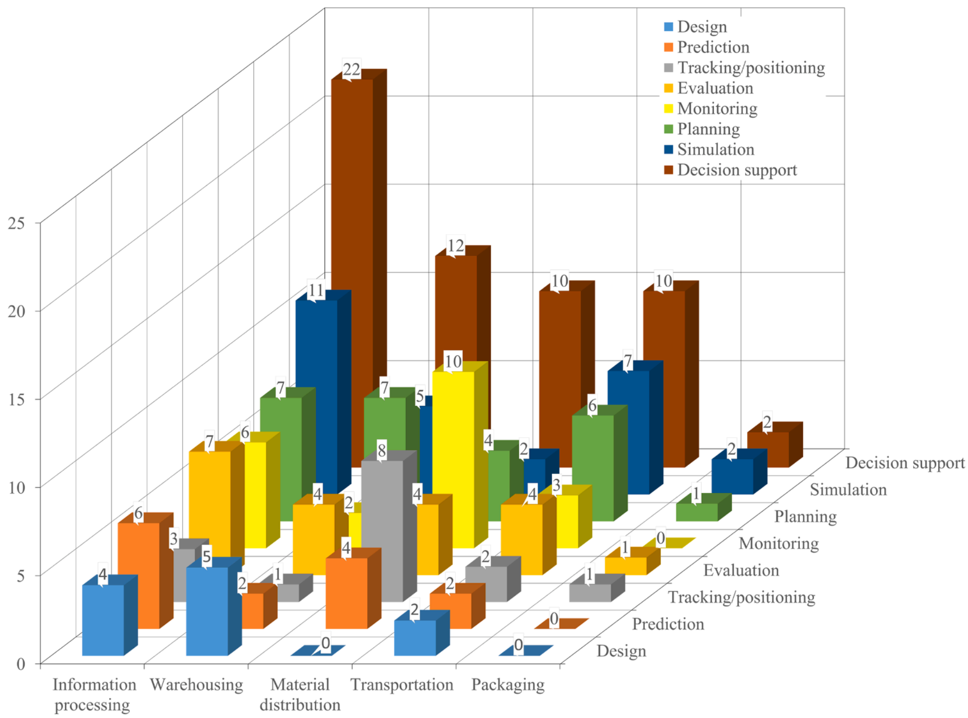

Fig. 7. Distribution of functions of DTs in PLAs (132 papers: 2017–2022).

"tracking/positioning" functions played by DTs in PLAs should not be overlooked, such as risk prediction of storage items [32], evaluation and testing of new logistics equipment [33], and visual positioning and tracking of logistics resources [34].

3. Detailed analysis of the functions of DTs in PLAs

Based on the results of the analysis of the PLDTs research profile, 132 publications are described in detail in this section from the perspective of PL application scenarios, including specific types of PLAs, research methods, main functions, intelligent technologies and validation approaches. The common application scenarios and basic functions of PLDTs, as well as related intelligent technologies, are summarized in Fig. 8, the purpose of this section is to provide a detailed overview of the latest and most advanced research in the application of DTs in the field of PL.

3.1. Applications of DTs in transportation

Transportation is an activity that runs through all phases of PL, mainly including logistics resources, transportation of semi-finished and finished goods. Therefore, the transport phase of PL plays a critical role in the overall productivity, product quality, and customer satisfaction. The roles played by DTs in PL transportation include transportation decision optimization, process simulation, real-time positioning/tracking, etc. These DTs-based approaches have been studied extensively by many researchers and are summarized in Table 2.

Synchronous decision-making is vital to the transportation process, which serves as a crucial component in the overall PL process and frequently interacts with other PLAs. However, transportation processes often encounter significant synchronization challenges, including information and physical synchronization, spatial-temporal synchronization, and decision synchronization. To address these issues, Pan et al. [35] proposed leveraging DT-driven decision information framework and a real-time dynamic synchronization control mechanism to realize the synchronization of PLS throughout the entire transportation stage. To achieve rapid synchronization decision-making for PL, Guo et al. proposed the concept of shop-floor production and logistics synchronization with four principles: synchronization-oriented manufacturing system, synchronized information sharing, synchronized decision-making, and synchronized operations. Furthermore, an overall framework of intelligent manufacturing system was proposed based on Industrial Internet of Things (IIoT) and DTs technology to support the synchronized decision-making of shop floor logistics and manufacturing.

Virtual testing of new equipment or logistics installations is a viable alternative to traditional physical testing, which can be costly and have significant limitations. To address these concerns, Hauge et al. [36] proposed a testbed for PLDTs to evaluate new Production Logistics Equipment (PLE) and infrastructures in a virtual space before they are put into service. This approach allows decision-makers to assess whether the newly-developed equipment or facilities can support relevant decision-making processes without incurring trial-and-error costs or other technical risks [37].

Historical transport process reproduction involves using historical operational data stored in a database to recreate PLDTs-based transport processes and states in virtual space. This approach can help identify and track bottlenecks and anomalies in the transport process [38,39]. Real-time positioning and tracking of the entire transportation cycle is another crucial application of PLDTs. Hauge et al. [40] employed a data-driven online simulation of PLDTs with real-time position information to enable effective tracking and positioning of PL resources throughout the transportation cycle.

3.2. Applications of DTs in packaging

Packaging plays a crucial role in the PL process, generally serving as a preceding stage to storage. It is the encapsulation or protection of the product for transportation and warehousing, as well as for subsequent sales, etc. During the flow of products from packaging to warehousing, problems such as packaging or warehousing stacking tend to occur, which seriously affects the overall efficiency of PL. Consequently, the implementation of DTs in the packaging stage concentrates primarily on real-time product positioning, visual traceability, resource planning and

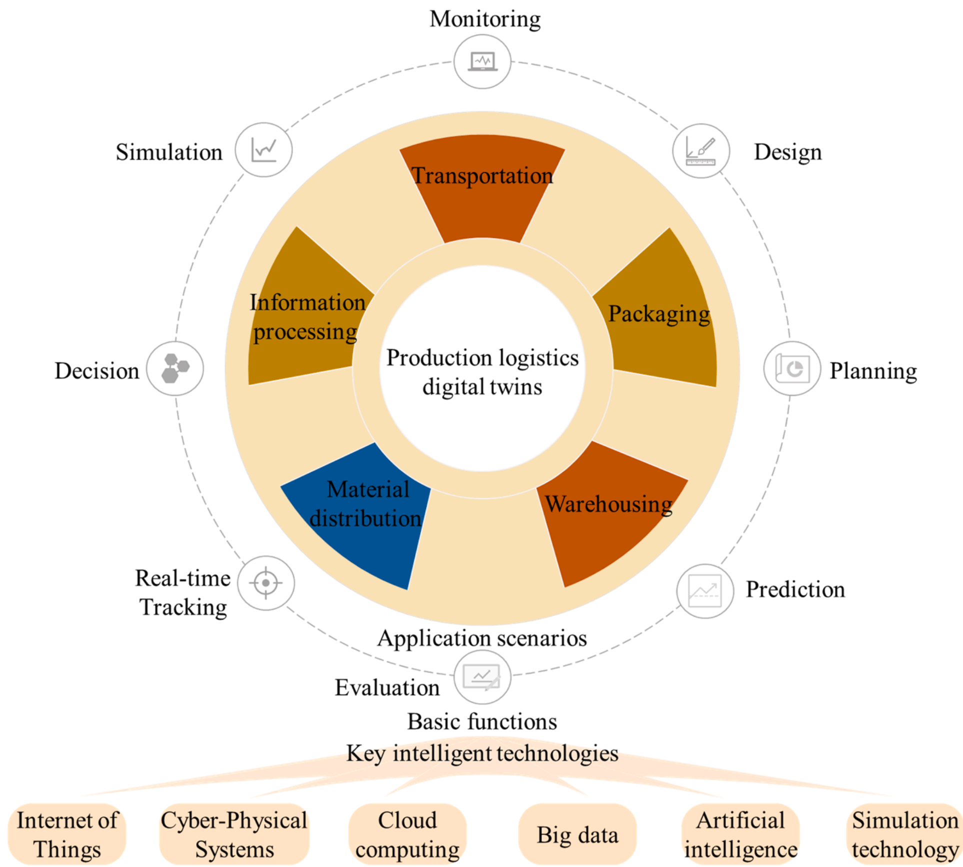

Fig. 8. Common application scenarios, basic functions and intelligent technologies of PLDTs.

process simulation, as well as collaborative optimization of both packaging and warehousing. Table 3 shows the application of DTs in packaging scenarios.

DTs possess the capability to facilitate cyber-physical synchronization while offering intelligent services for more efficient operations. Therefore, Wu et al. [41] developed a real-time tracking and tracing platform for finished goods logistics based on IIoT and DTs. It helps to achieve spatial-temporal traceability and visibility of finished goods logistics through information and physical synchronization, thus monitoring and optimizing product waiting times in packaging and other buffers. Marmolejo et al. [42] proposed the integration of large-scale optimization problems in a digital platform, such as solving bin packing and vehicle routing problems, and used technology based on Discrete Event Simulation (DES) to achieve the periodic decisions that make up the Digital Supply Chain Twin engine. Dąbrowska et al. [43] presented the limitations and advantages of implementing DTs in packaging line sequencing and planning problems, and the results of DTs simulations are used for decision-making in subsequent actions. Leng et al. [23] proposed DTs-driven joint optimization of packing and storage assignment in large-scale automated high-rise warehouse product-service system. With the help of powerful data analysis of simulation engine and optimization algorithm on the DTs system, it can not only generate warehousing plan for quantitative comparison but also can be used to optimize the packing solution for saving carton resources.

3.3. Applications of DTs in warehousing

Compared to other PLAs, warehousing system has the characteristics of large structure, complex environment, and frequent access to the warehouse [23]. Meanwhile, with the continuous emergence of large automated high-rise warehouses such as material warehouses, semi-finished goods warehouses and finished goods warehouses in the production shop-floor, the manufacturing industry has increased its requirements for the intelligence and flexibility of warehouse management systems, as well as the relatedness with other PLAs [44]. As shown in Table 4, some researchers have conducted related research on the application of DTs in PL warehouse management.

In terms of warehousing management, according to the bottleneck problem in warehouse picking operations, Cao et al. [45] proposed a warehouse management system based on DTs, a dynamic interactive picking path optimization method based on DTs has been formed, which effectively improves warehouse picking efficiency and overall operation level. Due to the complex legal requirements closely related to many daily PL processes, especially when dealing with dangerous goods. There are increasingly serious challenges in compliance, which require actions to manage compliance effectively and fully. Perez et al. [32] introduced the concept of DTs in the legal requirements for production and logistics, which can be used to evaluate the compliance of warehouse contents, employees and the environment. Petkovic et al. [46] used Virtual Reality (VR) digital warehouse twins in order to realistically simulate worker behavior, and tested the proposed algorithm for estimating the intentions of warehouse personnel. Bučková et al. [47] presented a method of implementation before, during and after the design of logistics systems using computer simulation and emulation, which can improve the speed and accuracy of picking of orders in warehouse.

Moreover, optimizing warehouse logistics in conjunction with other logistics activities profoundly contributes to the overall efficiency of PL, both in articulated and storage warehouse systems. For instance, focusing on the real-time linkage operation of three typical units of industrial park “production-transportation-warehousing”, Zhou et al. [44] proposed a cross-unit DTs linkage decision information architecture. The framework has realized global optimization and online linked decision-making for large systems. Harrison et al. [48] explored the use

Table 2
Application of DTs in transportation (24 papers: 2017–2022).

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Wang et al. (2018) [38]	-PLE -Shop-floor layout	-Adopted eM-Plant software to simulate and optimize the logistics of the virtual shop-floor	-Process simulation -Energy monitoring	-CPS	-Validated in an automotive gear machining shop-floor
D'angelo (2019) [65]	-Transportation	-Discussed the method of integrating DES modeling into the Reliability-Risk-IoT model to create a "logistics twin"	-Logistics modeling -Reliability-risk modeling	-DES -IoT	-Theoretical research
Hauge et al. (2020) [33]	-Physical equipment -Infrastructure	-Presented the usage of DTs for supporting the decision-making processes in two different areas: workstation design and logistics operation analysis.	-New equipment Evaluation	-CPS -IoT	-Tested on the laboratory platform
Hauge et al. (2020) [36]	-Physical equipment	-Built a PL testbed based on DTs, including physical devices, IoT infrastructure and simulation software	-New PLE Evaluation -Decision Support	-IoT -Simulation software	-Validation in a lab environment
Kim et al. (2020) [66]	-Assembly logistics -RCL	-Proposed a new intelligent manufacturing simulation framework based on DTs simulation	-Layout design -Live simulation -System integration	-VR -IoT -DES	-Tested by setting up specific logistics scenarios at the factory
Wang et al. (2020) [67]	-Transportation -RCL	-Carried out the design method of five-dimensional DTs model of Roller Conveyor Line (RCL)	-Process design -Distribution control	-CPS	-Laboratory platform validation
Gyulai et al. (2020) [68]	-PLE -PLS	-Proposed a DES model for shop-floor logistics based on DTs	-Strategy testing -Path planning -Scheduling decision	-DES	-Application testing in the semiconductor industry
Ait-Alla et al. (2020) [69]	-Transportation -Assemble	-Proposed a configuration method for interconnecting physical and twin systems	-Process simulation -Program validation	-DES -CPS -RFID	-Tested at a simulated scenario
Fottner et al. (2021) [9]	-AGV -Infrastructure	-Described the application outlook for virtualizing intralogistics using DTs	-Virtual simulation -Real-time monitoring	-RFID -AR	-Case description
Pan et al. (2021 [35]	-Transportation	-Proposed a DTs-driven decision information architecture, and developed a real-time dynamic synchronization control mechanism	-Path optimization -Synchronization control	-RFID/WSN/GPS	-Validation in an industrial park
Hauge et al. (2021) [40]	-AGV	-Constructed the system architecture of PLDTs, and discussed the corresponding application scenarios	-Path planning -Real-time tracking	-IoT	-Laboratory simulation validation
Bai et al. (2021) [70]	-PLE -Transportation	-Pointed out that DTs provides predictive analysis technical support for the upgrading of production lines	-Fault diagnosis -Predictive maintenance	-Blockchain -Genetic algorithm -IoT/RFID	-Simulation verification
Spitzer et al. (2021) [71]	-Intralogistics transportation system	-Established an internal control logic and corresponding DTs model generation framework	-Control logic generation -Path planning	-OPC UA -ST	-Tested at the Smart Manufacturing Center of the Austrian University
Guo et al. (2021) [72]	-PLE -Transportation	-Established shop-floor logistics and production synchronization mechanism based on IIoT and DTs	-Time optimization -Synchronization control -Information sharing	-VR -AR	-Tested at actual plant
Golova et al. (2021) [73]	-PLE -Transportation	-Presented a method for analyzing PL performance based on DTs simulation	-Improve efficiency -Feasibility analysis	-IoT -AI	-Validated at chemical manufacturers
Müller et al. (2021) [74]	-AGV	-Developed a mixed reality application, and used DTs to integrate manufacturing cells	-Process simulation -Virtual-real interaction	-MR -DES	-Validated by building test scenarios in the lab
Stączek et al. (2021) [75]	-AMR/AGV	-Built a virtual test environment for AGV/AMR based on DTs	-Algorithm testing -Safety function testing	-IoT -CC -CPS	-Conducted early stage testing in the shop-floor
Martínez-Gutiérrez et al. (2021) [76]	-AGV	-Proposed a new DTs design concept based on external service for the transportation of the AGVs	-Simulation and visualization -Trajectory planning	-CPS -CC	-Validated by building test scenarios in the lab
Deng et al. (2021) [77]	-Distribution management system	-Proposed the architecture of DTs-based distribution management system	-Boxing planning -Route optimization	-IoT	-Tested with distribution examples
Tao et al. (2022) [39]	-PLE	-Established DTs textile shop-floor PLE operation and maintenance control system	-Real-time monitoring -Virtual Simulation -Remote operation	-AI	-Validated in the textile shop-floor
Wu et al. (2022) [78]	-Transportation	-Presented a PLS architecture using IIoT and DTs technologies	-Product tracking -Product positioning	-LSTM -IIoT	-Tested at a computer manufacturing facility
Lim et al. (2022) [79]	-Transportation	-Leveraged DTs capabilities to propose a 4PL-oriented heuristics search model for omnichannel logistics planning and scheduling	-Enhance transportation flow -Enhance resource utilization	-CC -IoT	-Industrial case
Zheng et al. (2022) [80]	-Logistics distribution	-Presented a modeling and analysis method of temporal graph network model of PL, and established temporal graph network model of PL tasks in DTs system	-Intertask link relationship prediction -Autonomous scheduling of logistics distribution process	-Spatio-Temporal Graph Network	-Applied to a steel factory in Shanghai, China
Sun et al. (2022) [81]	-Semi-autonomous transportation	-The current and future research prospects of sustainable logistics in the era of Industry 4.0 are quantitatively analyzed and comprehensively summarized	-System integration	-IoT -CPS -AI -CC	-Theoretical research
Xiao et al. (2022) [82]	-Workshop logistics distribution -AGV	-Designed the conflict-free path planning algorithm based on the environment map twin model	-Path planning	-A*algorithm	-Simulation verification

Abbreviations not noted in Table 2 are as follows: Cyber-Physical Systems (CPS), Automated Guided Vehicle (AGV), Augmented Reality (AR), Autonomous Mobile Robot (AMR), Object Linking and Embedding for Process Control Unified Architecture (OPC UA), Simulation Technology (ST), Wireless Sensor Networks (WSN), Global Positioning System (GPS), Mixed Reality (MR), Long Short-Term Memory (LSTM).

Table 3
Application of DTs in packaging (5 papers: 2017–2022).

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Leng et al. (2021) [23]	-Packaging -Warehousing	-Proposed a DTs-driven joint optimization method for storage and packaging	-Synchronized decision	-CPS	-Validated at the tobacco warehouse
Marmolejo et al. (2021) [42]	-Packaging -Path planning	-Achieved cyclical decision-making in DTs supply chain based on DES	-Cyclical decision-making -Operation optimization	-DES	-Validated with hypothetical cases
Wu et al. (2022) [41]	-Packaging -Quality detection	-Developed IIoT and DTs based real-time tracking and tracing architecture for finished goods logistics	-Real-time tracking -Intelligent positioning	-IIoT	-Validated at a computer building factory
Dąbrowska et al. (2022) [43]	-Packaging -Transportation	-The concept of implementing digital twinning in analytical production process was proposed for packaging line sequencing and planning	-Sequencing and planning -Process simulation -State assessment	-IoT -AI -ML	-Taking sugar industry as a case study

of distributed warehousing and localized kitting systems within an Industry 4.0 framework in order to reduce non-value-adding activities within adaptable processes, so that product variety and volumes can by dynamically changed whilst maintaining efficiency. Furthermore, the integration of systems such as production, transportation and warehousing also offers advantages like determining types and amount of equipment needed to fulfill production plans, evaluating various alternative factory layout options in order to increase throughput and equipment utilization, investigating possible bottlenecks in movement of material flows, and assessing the impact of operator behavior on production performance [49].

3.4. Applications of DTs in material distribution

To satisfy the demand for instability caused by dynamic disturbances such as schedule adjustments, environmental changes and equipment failures, the dynamic planning of PL resources in real time to accommodate changes in the PL processes will become the new normal. [50,51]. As shown in Table 5, some researchers have conducted related research on the DTs-based PL resources distribution.

To address the challenges of visual tracking and real-time location of PL resources, Flores-García et al. [52] proposed an architecture for PL services based on DTs. The advantages of DTs-based real-time positioning and optimization services in material processing have been proved. Hegedűs et al. [34] proffered a tracking and management architecture for shop-floor and logistics resources using DTs services that incorporate high-precision indoor positioning and Radio Frequency Identification (RFID) tracking functions, enabling the comprehensive positioning and tracking of diverse resources throughout the whole shop-floor and logistics. For path planning concerns pertaining to material flow in complicated environments, Zhang et al. [53] proposed a DTs shop-floor based material just-in-time distribution method. The problem of uncontrollable path planning time in the hybrid environment has been solved effectively, the real-time synchronization of material distribution and processes has been ensured. In addition, the utilization of DTs lends itself to exhaustive 3D visualization and monitoring of individual components and systems [31]. For example, as a key element in the material flow of PL processes, the health monitoring of PLE in material distribution has been an issue of great concern. The real-time monitoring of PLE health state has been realized by relying on IoT technology to collect the state of each PLE in real time, and combining data mining, Machine Learning (ML) and Artificial Intelligence (AI) technologies, etc., [54].

Regrettably, there are still no clear guidelines for the design of PLDTs, the expected design results may not be achieved [55]. It may keep manufacturing companies from adopting a PLS design approach based on DTs [56]. To address these challenges, Jeong et al. [57] proposed a design process for PL based on the DTs five-dimensional model, which includes three phases: pre-study, concept and detailed design. The rational design and allocation of PL resources have been effectively realized. For the application of prediction function, a DTs shop-floor material distribution system has been constructed by Wang et al. [25], which has solved the problems of poor material distribution cycle time, redundant distribution routes and unpredictable material distribution demand time points.

3.5. Applications of DTs in information processing

Given the highly dynamic nature of its operating environment comprising diverse activities, the efficient operation of PL hinges on the systematic integration of logistics information and the judicious allocation of logistics resources [3]. In this regard, the application of DTs offers better decision-making support tools for information processing and operational aspects of PL [6,26], helping to foster a closed-loop chain among PL elements such as materials, products, PLE and each PLAs, thereby continuously improving overarching PL operations [58]. As collated in Table 6, numerous researchers have conducted comprehensive studies exploring the application of DTs in facilitating PL information processing.

In the design of PLS, due to the complexity and dynamics of the PL processes and the massive volume of logistics information, traditional design methods will make the design process of PLS to be unintuitive, time-consuming and non-repeatable , etc., [59]. The application of DTs provides a new way of ideas to solve the above problems. Murrenhoff et al. [30] proposed a DTs-based design method for intralogistics systems, including pre-design requirements analysis, iterative simulation and evaluation during the design process, and virtual-real connection and self-renewal after completing the design. It is an iterative, replicable, and continuously updated process that can inform the design of next-generation PLS. Straka et al. [60] adopted computer simulations to study and simplify large-scale logistics systems and conducted system evaluation and hypothesis validation based on DTs.

In the operations of PLS, by building a PLS based on DTs, the processing of PL information and the iterative simulation of the operational process can be carried out in virtual space. The simulation results can be used to make systematic and adaptive synchronization decisions for the PLS in physical space, thus ensuring the synchronization of the PL process at all stages. For example, Pan et al. [5] proposed a multi-level

Table 4
Application of DTs in warehousing (27 papers: 2017–2022).

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Avventuroso et al. (2017) [83]	-Warehousing	-Presented a new concept of a production system based on virtual factory replication development	-Warehouse design -System optimization -Information sharing	-IoT −3D scanner	-Tested at the factory
Korth et al. (2018) [84]	-Warehousing -Resources planning	-Built a real-time management and decision support system for PL based on DTs	-System design -Operations management	-ML	-Worker shift schedule testing -Tested at a medium-sized metalworking company
Bohács et al. (2018) [85]	-Warehousing	-A new intralogistics control structure between centralized and distributed based on DTs	-Process simulation -Decision prediction	-CPS -IoT	-Case description
Ashrafian et al. (2019) [24]	-Warehousing	-Built a large warehouse conveyor operation decision and optimization system	-System design -Decision optimization	-DES	-Laboratory simulation validation
Zhou et al. (2019) [44]	-Warehousing	-Proposed cross-unit linked decision-making information framework for industrial parks	-Linkage control -Collaborative control	-RFID/WSN/GPS	-Verified at a chemical manufacturing company
Petkovic et al. (2019) [46]	-Warehousing -PL operators	-A warehouse model of DTs was constructed to validate the proposed algorithm	-Behavior simulation -Virtual testing	-AR	-Compared with real experimental results
Bučková et al. (2019) [47]	-Warehousing	-Proposed a PLS design scheme using DTs simulation and emulation	-PLS pre-design, design and post-design simulation	-ST	-Experimental verification
Harrison et al. (2019) [48]	-Warehousing	-Built an adaptive system architecture that integrates intralogistics, assembly and distributed warehousing	-PL dynamic integration	-AI/ML -CC	-Tested on the laboratory platform
Iureva et al. (2019) [49]	-Warehousing	-Built DTs-based virtual test platform for internal logistics in assembly plants	-Simulation testing -Bottleneck analysis	-CPS	-Laboratory simulation validation
Ding et al. (2019) [86]	-Warehousing	-Proposed a definition of digital twin supply chain	-Equipment management -Transport monitoring	-IoT	-Case description
Nikolakis et al. (2019) [87]	-Warehouse operations -PL workers	-Planning and commissioning of human-based production processes based on DTs simulation	-Human resources planning -Station design -Rapid prototyping	-CPS	-Application verification in the white goods industry
Guerreiro et al. (2019) [88]	-Warehousing	-Proposed a big data architecture based on DTs that is easy to deploy and reconfigure	-Process planning -Performance analysis	-VR -Sensor technology	-Validated in the automotive battery assembly processes
Perez et al. (2020) [32]	-Warehousing	-A DTs-based warehouse material safety assessment method is proposed	-Cargo safety assessment -Security management	-WSN -CPS	-Theoretical research
Chen et al. (2020) [89]	-Warehousing	-Established a unmanned aerial vehicle warehouse management system based on DTs and cloud platform	-Management unmanned -Information visualization -Remote monitoring	−5 G -RFID -UWB	-Conducted simulated experiments in a laboratory environment
Agalianos et al. (2020) [90]	-Warehousing	-Pointed out that DTs facilitate the convergence of physical and virtual warehouses	-Rapid planning -Efficient control	-DES -IoT -AI	-Theoretical research
Jagtap et al. (2020) [91]	-Warehousing	-Discussed the key technologies, opportunities and challenges of DTs simulation in the application of Food Logistics 4.0	-Resource planning -Warehouse management -Transport management	-Industry 4.0 Technologies	-Case description
Figueiras et al. (2021) [92]	-Warehousing	-Introduced DTs-based logistics processes development and deployment solution for the automotive industry	-Process planning -Inventory optimization -Performance evaluation	-Big data -ML -CPS	-Laboratory simulation validation
Cao et al. (2022) [45]	-Warehousing	-Designed and built DTs model of the entire operation processes of the warehouse	-Route planning -Improve efficiency	-ST	-Validated at a warehouse
Yao et al. (2022) [93]	-Warehousing	-Proposed an intelligent storage and retrieval system based on DTs for logistics automation warehousing	-Logistics automation -Simulation	-CPS -SVM	-Experimental testing
Guo et al. (2022) [94]	-Warehousing	-The application prospects of DTs in PLAs were analyzed based on the practical applications of DTs	-Real-time tracking -Decision basis	-CPS/IoT -AI	-Case description
Tang et al. (2022) [95]	-Warehousing	-Built a DTs model for small industrial smart warehouses	-Demand forecasting -Inventory optimization	-Genetic algorithm	-Tested in small-scale textile companies
Zhang et al. (2022) [96]	-Warehousing	-Presented a model framework of smart shop-floor manufacturing system based on DTs	-Improving utilization -Enhancing efficiency -Cost reduction	-Big data -AI	-Validated in the textile shop-floor
Ramirez et al. (2022) [97]	-Warehousing	-Performed the essential steps to implement a basic 5 G DTs in a warehouse scenario, and provided a paradigm of end-to-end connection and encryption to IoT devices.	-End-to-end communication	-IoT −5 G	-Theoretical research
Ferrari et al. (2022) [98]	-Warehousing	-Presented a DTs proposal for a real-world AS/RS system, highlighting its current implementations together with its future developments.	-Stock control -High space utilization	-DES -AI	-Logistics laboratory test
Chakroun et al. (2022) [99]	-Warehousing	-Characterized and analyzed the transformation 4.0 process adopted by a factory producing spherical bushels	-Material requirement planning -Real-time management of logistics warehouse	-AI	-Tested in a factory producing spherical bushels

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Table 4 (*continued*)

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Chakroun et al. (2022) [100]	-Warehousing	-Set up a simulation tool to develop a numerical production platform for Industry 4.0 which is able to efficiently manage the production and procurement through logistics warehouse	-Improve equipment utilization rate -Strengthen management	-CPPS	-Tested at a workshop producing brass accessories
Berti et al. (2022) [101]	-Inventory management	-The proposed supply chain digital twin framework integrates ML and simulation to identify the inventory replenishment policies	-Inventory management -Simulation	-Decision tree algorithms -ML	-Simulation experiment verification

Abbreviations not noted in Table 4 are as follows: 5th Generation Mobile Communication Technology (5 G), Ultra Wide Band (UWB), Support Vector Machine (SVM), Cyber-physical Production Systems (CPPS).

cloud-based DTs system for real-time monitoring and synchronized decision-making in PLS. From the perspective of information-physical synchronization, space-time synchronization and data-driven decision-making synchronization, the concept of Operation Twins was proposed by Li et al. [20]. Helped to realize synchronized operational management of PL.

Additionally, PLDTs can be used for parallel monitoring of multiple PLAs [61]. It helps to organize the monitoring and control tasks of the PL processes more effectively to take full advantage of the data. Based on DTs and ML, an integrated framework linking PL processes has been presented by Greis et al. [62], which ensured the adaptive scheduling of production processes and the flexible operation of logistics processes. The PLE DTs was established in the virtual space by Guo et al. [63] to synchronize the real-time state data and dynamic behavior of the corresponding logistics equipment. Provided accurate state information for efficient execution of PLS. To address the inefficiency of logistics caused by the combination of many people and machines, Löcklin et al. [64] constructed a human-centered DTs architecture. Behavior, intent and location information of intralogistics operators can be predicted, which helps to develop and reuse human-centered solutions.

4. The role of intelligent technologies in PLDTs

Based on the classification statistics in Table 2–6, it can be seen that the construction and application of PLDTs require the support of intelligent technologies such as IoT, CC, and big data. Combining with the specific application cases of these intelligent technologies in the PL context, this article focuses on their possible roles in PLDTs. In this section, six intelligent technologies are discussed, including IoT, CC, big data, AI, simulation, and CPS.

1. **Internet of Things.** IoT is the basis of the development and application of PLDTs. Using RIFD tags, WSN, actuators, etc., enables information about various PL resources in the physical world to be sensed and controlled [35]. We focused on the role of IoT in PL state sensing and virtual-real interconnection.
   (i) State sensing based on RFID tags. RFID tags are used to identify and capture PL data by attaching them to the surface of PL resources such as boxes, warehouse shelves and products. For example, Wu et al. applied UWB tags to finished products and transportation equipment, and combined with DTs to achieve temporal and spatial traceability and visibility of the logistics transportation process of finished products on the shop-floor [78].
   (ii) Virtual-real interconnection based on multi-WSN. Because sensors in WSN communicate wirelessly and sensor nodes can be freely combined. Therefore, WSN is flexible in addressing virtual connectivity. Some researchers have constructed multiple WSNs to monitor the state of PLE in real time, which has enabled resource location during material distribution [52] and product quality tracking [34], as well as real-time identification of PLE state during information processing [30,127].

   From this it can be inferred that IoT enables the PLDTs system to real-time perceive and control the PL resource information in the physical world. All physical and virtual resources collaborate and interact autonomously through the IoT, ensuring the physical and virtual connectivity. The similar conclusion was also reached in [9].
2. **Cloud Computing.** PLS is a dynamic and large-scale system, covering multiple independent decision-making and interrelated subsystems. To address the issue of potential information silos, utilizing CC to integrate and share PLS information resources appears to be an effective approach. CC plays the following roles in the PLDTs system.
   (i) Cloud storage of PL information. At present, most of the servers for IoT are deployed in the cloud, and CC technology can provide powerful cloud storage space for massive PL data [103].
   (ii) Fast computing power. As an extension of CC, EC has provided high-efficiency computing power for synchronous decision-making in PLDTs system [5,109].
   (iii) Online sharing of PL information. CC supports the sharing of configurable computing resources, allowing operators to access PL information over the network anytime and anywhere as needed. It can rapidly provision and release PL resources with minimal management effort or service [127].

   Based on the above analysis, the CC technology has provided online integration and rapid computing capabilities for resource information of the PLDTs system [26]. It not only satisfies the demand of PLDTs system for massive data storage, but also lays the platform foundation for subsequent data resource sharing.
3. **Big Data.** Big data technology can mine new PL business value through large-scale PL information collected by IoT combining with CC technology, which will promote the development of PLDTs. It has the following application scenarios in PLDTs system.
   (i) Data visualization. Big data is not only the foundation of data visualization provided by the PLDTs system, but also the key to ensuring the interaction between virtual and physical spatial logistics activities [108].
   (ii) Virtual model construction. The accuracy of the construction of the virtual world PLDTs system, and the correlation with the physical world PLS depends on the quantity and quality of big data [88].
   (iii) PL process reproduction. Based on the historical operation data stored in the database, the process and state of historical PLAs can be reproduced, historical faults and abnormal problems can be traced [39,88].
4. **Artificial Intelligence.** AI technology plays an indispensable role in accurately interpreting and analyzing data from PLDTs system, allowing for flexible utilization of data analysis results to achieve specific goals and tasks and thereby enhance the intelligence of these systems [153]. Common AI algorithms include traditional ML [129], RL [22], and the new generation of ML algorithms represented by DL [126]. The application of AI technology in various PLAs will accelerate the development of PLDTs, which has thus drawn significant attention from researchers. The applications of AI technology in various PL scenarios are as follows.

Table 5
Application of DTs in material distribution (31 papers: 2017–2022).

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Venkatapathy et al. (2017) [102]	-Material handling	-Built a human-machine collaborative hybrid network for intralogistics based on technologies such as CPS, IoT and DTs	-Scenario simulation -Human machine interaction -Positioning -Tracking	-CPS -IoT	-Research Center (Under construction)
Zhang et al. (2018) [103]	-Resource allocation	-Built a DTs-driven smart shop-floor architecture, and designed a dynamic resource allocation scheme	-Dynamic resources allocation and tracking	-CC/AI -RFID/IoT	-Validated with factory cases
Hegedűs et al. (2019) [34]	-Logistics asset management	-Presented a tracking and management architecture for logistics resources based on DTs	-Resources tracking -Indoor positioning	-UWB/RFID -WiFi	-Performed proof of concept at demo system
Efthymiou et al. (2019) [104]	-Material handling	-Analyzed the impact of DTs and Industry 4.0 technologies on intralogistics	-Material tracking -Information flow support	-VR -RFID/IoT -Big data	-Case description
Wang et al. (2020) [25]	-Material handling	-Built a shop-floor DTs model and proposed a residual processing time prediction method for work-in-process	-Performance prediction -State mapping -Path optimization	-IoT -CPS	-Tested at tire mold manufacturers
Zhang et al. (2020) [53]	-Material distribution -Satellite assembly	-Presented a DTs satellite assembly shop-floor material distribution method on time	-Path planning -Time prediction	-Gray theory	-Validated in the satellite final assembly shop-floor
Jeong et al. (2020) [57]	-Resource allocation	-Presented a design flow for five-dimensional PLDTs	-Resource allocation -Decision support	-Systems engineering	-Laboratory platform validation
Kosacka-Olejnik et al. (2021) [10]	-Internal transport -Material handling	-Discussed the main research trends and future research directions of DTs in internal transport systems	-Virtual-real interconnection -Dynamic monitoring	-CC -IoT -Big data -AI	-Case description
Hiller et al. (2021) [31]	-Order handling -Distribution	-Proposed a method for continuous calculation of backlog and output based on DTs	-Distribution monitoring -Improve efficiency	-Big data -ST	-Application in optoelectronic production
Flores-García et al. (2021) [52]	-Material handling	-Proposed a framework for intelligent PL services based on DTs and IIoT	-Resources locating -Path optimization	-IIoT	-Demonstrated at an automotive company
Stan et al. (2021) [54]	-Resources distribution -Robot palletizing	-Data-driven DTs and model-driven DTs were constructed separately for PL resources	-PLE monitoring -Process simulation	-ST	-Validated using simulation experiments
Coelho et al. (2021) [105]	-Intralogistics system	-Presented a DTs architecture for intralogistics and developed a decision support tool for intralogistics based on DTs simulation	-Operation planning -Decision support	-Virtual system -ST	-Tested in logistics supermarkets and automotive manufacturing
Lee et al. (2021) [106]	-Material handling	-Presented an automatic material handling system based on DTs	-Transport monitoring, -Diagnosis and prediction	-Industry 4.0 technologies	-Validated at the manufacturing company
Kim et al. (2021) [107]	-Material handling	-Discussed the impact of DTs-driven distribution services on the economic, environmental and social sustainability of smart PL	-Improve performance -Real-time positioning -Predictive service	-RFID -UWB -DES	-Presented a case form an automotive company in Sweden
Guo et al. (2021) [108]	-Material handling -AGV	-Presented a flexible cell manufacturing method based on DTs	-AGV layout optimization -Equipment testing -Path optimization	-Big data	-Validated in the air conditioning line
Lei et al. (2021) [109]	-PL resource management	-Proposed a cloud-side collaborative planning and shop floor logistics scheduling framework	-Process monitoring -Resource scheduling	-CC/EC -RFID -IIoT	-Theoretical research
Zhao et al. (2022) [110]	-Resource allocation	-Proposed a logistics resource allocation method based on dynamic spatial-temporal knowledge graph	-Distribution decisions -Resources monitoring	-DNN -IoT	-Tested at an air conditioning manufacturing company
Wang et al. (2022) [111]	-Material distribution	-Built a PLS control model and full-cycle material distribution mechanism based on DTs	-Delivery time forecast -Path optimization	-LSTM	-Tested in the asynchronous card line shop-floor
Ko et al. (2022) [112]	-Modeling	-Supply chain process is modeled based on the concept of DTs	-Seamless connection -Visibility and efficiency	-IoT	-Theoretical research
Follath et al. (2022) [113]	-Process modeling	-Presented a process model for the creation of a DTs in the area of production and logistics	-Use-case classification	−3D simulation	-Theoretical research
Uhlenkamp et al. (2022) [114]	-Modeling	-Aimed to contribute to the formalization and standardization of the description of DTs, and presented a method for evaluating them through their lifecycle, from design to operation	-System optimization and evaluation	-AI	-Case verification
Hofmann et al. (2022) [115]	-Modeling	-Presented an intuitive and practice-oriented procedure model for deploying DES models on AWS	-DTs model development	-DES -Cloud platform	-Case demonstration
Lim et al. (2022) [116]	-Ergonomic risk assessment	-The real-time postal training effects on single and multi-person ergonomical risk scores are studied	-Real-time ergonomic risk assessment	-Sensor technology	-Laboratory testing
Nguyen et al. (2022) [117]	-Process planning	-Based on literature review, the relationship between DTs and physical Internet in supply chain management is summarized	-Real-time monitoring and evaluation	-Physical Internet	-Theoretical research

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Table 5 (*continued*)

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Zuhr et al. (2022) [118]	-Process planning	-Proposed the framework for planning and implementation of digital process twins in the field of internal logistics.	-Internal logistics process planning -Structural guidance during planning	-IoT -AI	-Tested in logistics planning
Borangiu et al. (2022) [119]	-Resource allocation	-Described an intelligent logistics model where the scheduling and resource allocation of logistics activities are optimized	-Monitoring and scheduling of logistics resources -Re-assigning jobs	-CC -PLC	-The main constructs are validated on a real-life structure with multiple palletizing resources
Nicola et al. (2022) [120]	-Ergonomic risk assessment	-Investigated the current state of the art in DTs and its application as a tool to evaluate and integrate ergonomic aspects, or additional human factors, in M&L systems	-System integration -Ergonomic risk assessment	-AR/VR -AI	-Theoretical research
Wang et al. (2022) [121]	-Resource allocation	-Proposed a real-time resource allocation method based on DTs for hull part smart picking and processing system	-Real-time resource allocation -Parts picking and processing	-DES -IoT -PSO -RFID	-Experimental tests are carried out in case studies.
Pivnička et al. (2022) [122]	-Human resources planning	-Presented a solution for better coordination of internal logistics processes and utilization of logistics staff based on discrete-event simulation	-Cooperation between production and logistics -Human resource management	-DES	-Case description
Ganesh et al. (2022) [123]	-AGV/Co-bots -Material handling	-Design and developed a DTs framework for a fleet of AGVs providing modularity and concurrent processing capability	-Improve the logistical efficiency	-IIoT -IoT -Machine vision	-Simulation experiment verification
Jeong et al. (2022) [124]	-Material handling	-Presented DTs-based services, and data visualization of material handling equipment in smart PL environment	-Data visualization	-IIoT -CPS	-Validated in the automotive industry

Abbreviations not noted in Table 5 are as follows: Wireless Fidelity (WiFi), Edge Computing (EC), Deep Neural Network (DNN), Programmable Logic Controller (PLC), Particle Swarm Optimization (PSO).

(i) Intelligent transportation. AI is beneficial to PL transportation. By using AI algorithms, the autonomous planning of routes, intelligent positioning and traceability of transport equipment such as AGV/AMR, and automated task handover can be achieved. This will improve transportation efficiency [78].

(ii) Packaging management. By calculating the demand plan for packaging materials, such as cartons and pallets, using AI algorithms, the rational sequencing and planning of the packaging line can be achieved [23,43].

(iii) Warehousing management. Through AI algorithms, reasonable plans for inbound and outbound scheduling, storage allocation, and intrawarehouse adjustment can be arranged to improve the flexibility and agility of warehouse systems. Leng et al. used a semi-physical simulation based on DTs system to verify the implementation effect of the periodic optimization decision-making method in warehouses, which can maximize the utilization and efficiency of large automated three-dimensional warehouses [23].

(iv) Self-distribution of material. The combined application of intelligent technologies such as AI, DTs and IoT can help accurately represent and visualize production logistics resources, fully considering the spatiotemporal dynamics of PL resources and their close integration with operations. For example, IoT signals data generated from large-scale deployed IoT devices are investigated and analyzed to spatial-temporal values through deep neural networks, resulting in the effective allocation of PL resources [110,111].

(v) Information processing. AI technology is capable of efficiently processing PL information and significantly reducing the cost of information processing. DL has become the preferred solution for extracting critical knowledge in PL state analysis and decision-making processes, due to its ability to perform in-depth feature extraction from big data, fit complex structured data, and map nonlinear data [62].

3 **Simulation Technology.** From the widely accepted definition of DTs [154], it can be inferred that virtual simulation is a fundamental function of DTs. And combining new IT technologies such as AI, CC, big data and digital modeling technologies to solve the problems in PLS. Thus, ST plays a crucial role in the PLDTs system, encompassing testing new PLE, conducting virtual experiments, and validating theoretical methods, among other aspects. For example,

(i) Functional Testing of New PLE. Hauge et al. proposed a DTs-based PL testbed that can be used for testing new physical devices, IoT infrastructure, and simulation software [36]. Stączek et al. noted that testing AGV/AMR control algorithms and functions in DTs-based virtual environments can accelerate real-time automation of PLS and reduce its costs [75].

(ii) Theoretical methods and scheme testing. Petković et al. verified the usability of the proposed methods and framework by employing virtual reality digital warehouse twins [46].

(iii) Risk assessment. Perez et al. proposed a DTs-based warehouse material safety assessment method [32]. Therefore, the application of ST in PLDTs system provides a virtual laboratory for users. Iterative simulation allows for the study of the effects of changes in the states of one or more PLAs on the PLDTs system, which is difficult to accomplish in physical space.

4 **Cyber-Physical Systems.** CPS aims to achieve perfect mapping and deep integration between cyberspace and physical space. Based on the integration of multiple technologies such as IoT, CC, and DTs, CPS provides an architectural foundation for the integration of PLDTs system [69,140]. The possible roles of CPS in the PLDTs system are as follows.

(i) Multi-system integration. Bohács et al. proposed a new control architecture between centralized and distributed based on CPS and DTs, which has opened up new possibilities for multi-system integration and local control of logistics processes [85].

(ii) Multi-technology collaboration. By building modular CPS systems capable of storage, analysis, processing and communication. IoT and CC are used to collect and process state data of PL processes in the physical space in real time [63,139]. And combining DTs models and AI algorithms for iterative simulation and optimization of PL processes [141].

Table 6
Application of DTs in information processing (45 papers: 2017–2022).

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Weigert et al. (2017) [125]	-Warning system	-Proposed a logistics process material flow online simulation, planning and control method based on DTs	-Process simulation -Operational decisions forecasting	-Online simulation	-Theoretical research
Zeidler et al. (2017) [126]	-Intralogistics system	-Described a research center that was used as an innovative service for intralogistics	-Scenario simulation -Human machine interaction	-CPS -VR -DL	-Research Center (Under construction)
Brenner et al. (2017) [127]	-PLS	-DTs could provide the latest state of required information, methods and algorithms for all subsystems	-Scene Simulation -Positioning	-CC -RFID	-Tested at the University of Reutlingen
Furmann et al. (2017) [128]	-PLS	-A digital copy of the real logistics was constructed based on DTs	-Parameter adjustment -Material handling	-IoT -Genetic algorithm	-Tested at CEIT and EdgeCom
Murrenhoff et al. (2018) [30]	-Intralogistics system -Warehousing	-Proposed a new concept of digital design for intralogistics based on DTs	-Guiding PLS redesign -PLS evaluation	-RFID -IoT -VR	-Case description
Kuehn et al. (2018) [58]	-PLS -Asset management	-A data- and model-driven multi-criteria decision-making approach based on DTs was proposed	-Operation management -Performance management	IoT	-Theoretical research
Straka et al. (2018) [60]	-PLS	-Analyzed the potential of computer simulations, using DTs simulations can simplify large-scale PLS	-System design -Iterative validation	-ST	-Verified in the automotive industry
Weigert et al. (2018) [129]	-Warning system	-Developed a PL simulation and early warning system based on DTs with DES coupled with AI	-Logistics simulation -Process warning	-NN -DES	-Laboratory simulation validation
Li et al. (2019) [130]	-PLS	-DTs-based, the techniques of production line model establishment and fusion, virtual-real mapping and interaction virtual production line simulation and verification were studied.	-Layout simulation -Virtual validation	-AI -ML	-Example of part processing
Moritz et al. (2019) [131]	-Intralogistics system	-Short-cycle and holistic planning of intralogistics systems by using the “digital design” approach	-PLS design -Layout planning	-VR	-Theoretical research
Schadler et al. (2019) [132]	-PLS	-Pointed out that DT-based predictive maintenance is the core innovation of Industry 4.0	-Predictive maintenance -Maintenance planning	-Knowledge database	-Theoretical research
Kavka et al. (2019) [133]	-PL teaching	-Demonstrated a DTs-based approach to PL virtual teaching services	-Virtual teaching	-IoT	-Validated at the School of Logistics
Piancastelli et al. (2020) [6]	-PLS	-Proposed the basic architecture of LDT	-Operational decisions -Risk assessment	-IoT −5 G	-A Fulfilment Centre was used for testing
Park et al. (2020) [18]	-Cyber physical logistics system	Proposed a cyber-physical logistics system based on DTs	-Distributed simulation -Mass customization -Supply chain control	-CPS -CPLS	-Tested at car manufacturing companies
Jiang et al. (2020) [26]	-PL service system	-Proposed a digital-twin-based implementation framework of production service system for highly dynamic PL operations	-Dynamic capture -Operational precision -Virtual simulation -Iterative decision	-IoT -CC	-Validation in paint chemical companies
Guo et al. (2020) [63]	-PLS	-Presented an adaptive synergistic method for PLS based on CPS and DTs	-Intelligent Control -Co-optimization	-CPS -IIoT	-Simulated validation at an aero-engine manufacturer
Dolgov et al. (2020) [134]	-PLS	-Developed a structural model of PLS based on DTs	-PLS planning -PLS behavior analysis	-ST	-Case description
Grigoriev et al. (2020) [135]	-PLDTs system	-Given the structural model of the PLDTs system, the data structure of the PLS information model was developed	-Problems of engineering activity -Complete solution of tasks -Tasks of operating activities - -Risk assessment	-CAE/CAM/PDM	-Theoretical research
Flores-García et al. (2020) [136]	-PL performance	-Highlighted the importance of DES in DTs, showed that the use of DES may facilitate the development of DTs	-Improve PL performance	-CPS -DES	-Tested at a Korean manufacturing company
Sommer et al. (2020) [137]	-Shop-floor layout planning	-Proposed a method for automatic generation of DTs models in the built environment, which provided manufacturing enterprises with room for improvement of production and logistics processes	-Process planning -Object identification -Layout optimization	-DES -CPPS -IoT	-Laboratory simulation validation
Pan et al. (2021) [5]	-PL synchronization system	-Proposes a multi-level CC enabled DTs system for the real-time monitor, decision and control of a synchronized PLS	-Synchronization control -Health Monitoring	-CC/EC/FC	-Validated at paint companies
Pawlewski et al. (2021) [8]	-PLS	-Proposed the concept of digital twin lean intralogistics, and pointed out the new trend of using DTs to simulate and optimize intralogistics processes in the future	-Process simulation	-IoT -CPS -Big data	-Case description
Grigoriev et al. (2021) [19]	-PLS	-Constructed the structural model of PLDTs system, and developed the data structure of PLS information model	-Simulation, evaluation and forecasting of PLS	-Big data	-Tested at mechanical engineering company
Li et al. (2021) [20]	-Intralogistics system	-Introduced a new concept of operations twins to realize PL synchronized operations	-Synchronized operations -Visibility and traceability -Operation management	-IoT	-Examples of hypothetical scenarios

(continued on next page)

Table 6 (*continued*)

References	Types of PLAs	Research methods or theories	Major capabilities	Intelligent technologies	Applications
Abideen et al. (2021) [22]	-PLS	-Proposed a conceptual framework of PL for data-driven DTs and Reinforcement Learning (RL) integrated applications	-Scenario simulation -Supported decisions	-RL -IoT -Big data -Blockchain	-Case description
Andronie et al. (2021) [61]	-Production System	-The DTs is leveraged for supervising and parallel monitoring of the manufacturing system, enabling online upgrade of the cyber-physical production system	-Process monitoring -Networking upgrade	-AI -IoT -Big data	-Case description
Greis et al. (2021) [62]	-PLS	-Proposed an integrated framework for connecting PL processes based on DTs and ML	-Risk Forecast -Flexible operations	-ML	-Theoretical research
Löcklin et al. (2021) [64]	-PL workers	-Presented a human-centered architecture for DTs	-Behavior, location and intent prediction -Visual feedback	-WLAN/UWB −5 G	-Theoretical research
Nitsche et al. (2021) [138]	-PLS -Co-bots	-Pointed out the potential of DTs in PL management	-Data management -Simulation and evaluation -Risk prediction	-CC -IoT	-Theoretical research
Vachálek et al. (2021) [139]	-PLS	-Constructed a generic information physical model based on DTs and CPS	-Algorithm tuning -PLS testing	-CPS -RFID	-Validated by building test scenarios in the lab
Xia at al. (2021) [140]	-Factory DTs system	-Analyzed the impact of factory DTs system, product DTs system and supply chain DTs system DTs manufacturing ecosystem construction	-Supply chain planning -Assisted design -Logistics layout planning	-CPS -VR -AR	-Validated at the hydraulic plant
Andronie et al. (2021) [141]	-Cyber-physical production system	-Explored how technologies such as DTs can effectively assist in PL processes planning	-Improving process -Improving efficiency	-CPS -AI	-Case description
Pan et al. (2021) [142,143]	-PLS	-Pointed out that DTs will be a new way to address digital interoperability models in PL management	-Enhancing interoperability -Improving performance	-LSCM -CPS -Blockchain	-Case description
Kuo et al. (2021) [144]	-PLS	-Pointed out that DTs make PLS more efficient and sensitive	-Synchronization control -Visualization	-IoT -VR	-Case description
Malindžak et al. (2021) [145]	-PLS -Order handling	-Designed order logistics automation processes based on DTs	-Layout optimization -Capacity planning	-AI	-Theoretical research
Kaiblinger et al. (2022) [1]	-PLS	-Discussed common definitions of DTs in the field of PL, and suggested potential research directions for PL based on case evaluation	-Mechanical maintenance -Operations monitoring	-CPS -IoT -AI -DES	-Case description
Thürer et al. (2022) [7]	-PLS	-Constructed a new architecture for PLDTs	-Visualization -Automatic response	-PLC	-Validated by building test scenarios in the lab
Battini et al. (2022) [146]	-Full-body ergonomic assessment	-Introduced a DTs platform for full-body ergonomic assessment and visual feedback in manufacturing and logistics systems	-Ergonomic assessment -Visual feedback	-Motion-capture -AR	-Validation in a lab environment
Wang et al. (2022) [147]	-Production scheduling system	-The virtual-real integration technology of DTs is used to integrate the information flow and logistics in the scheduling process to realize real-time coordination of information flow and logistics	-Real-time synergy between the information and logistics flows	-Virtual-real fusion	-Verified in frame shop.
Greis et al. (2022) [148]	-PLS	-Developed a framework integrating production and logistics processes that employs a ML-enabled DTs to ensure adaptive production scheduling and resilient supply chain operations	-Adaptive production scheduling –Resilient supply chain operation	-AR -ML	-Theoretical research
Sun et al. (2022) [149]	-Cyber-Physical Intralogistics Systems	-The system description defined the structure of the DTs and the communication of physical and logical assets	-Intralogistics Systems testing	-CPS	-Building an experimental environment
Ran et al. (2022) [150]	-Logistics management 3D scheduling system	-Proposed a framework that combines DTs with 3D visualization techniques to address real-time data interaction, component integration, and restoration of reality	-Logistics management and scheduling	−3D visualization	-Tested at a factory in Shandong
Krenczyk et al. (2022) [151]	-PLS	-Proposed schemes for data exchange in the process of creation and simulation models and mapping of the dynamics of the actual system are shown	-System integration -Virtual equivalence -Digital simulation	-CPS	-Theoretical research
Qiao et al. (2022) [152]	-Linkage decision	-Designed and verified a DTs-enabled P-D logistics linkage-oriented decision-making mechanism	-Collaborative optimization	-DL	-Enterprise verification

Abbreviations not noted in Table 6 are as follows: Deep learning (DL), Neural Network (NN), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), Product Data Management (PDM), Fog Computing (FC), Wireless Local Area Network (WLAN), Least Squares Conformal Maps (LSCM).

Moreover, the integration of VR/AR/MR, blockchain, 5 G and other technologies have been applied to enhance the reliability and feasibility of PLDTs system in industrial applications. For example, literature [66] combined VR technology for virtual training of PLS. In the literature [46], AR was used for accurate positioning of PLE. Literature [74] used MR technology to visualize the whole PLS. The implementation of blockchain technology in PLDTs system has proven instrumental in reducing instances of data breaches and fortifying overall security measures [70]. Furthermore, the communication capabilities of PLDTs system have been substantially augmented by the advent of 5 G technology [89].

5. Advantages and challenges of DTs application in PL

5.1. Advantages

Based on the analysis in chapters 3 and 4, it can be cleared that the integration of DTs with technologies such as IoT, CPS, and CC, enables PLDTs to have capabilities for monitoring, simulation, and prediction. This provides a comprehensive platform that can monitor and visualize, expand functions and integrate technologies for PLAs such as transportation, warehouse management and packaging [155]. To highlight the application advantages of DTs in the PL field, this section summarizes four general benefits of PLDTs, including data-model fusion-driven, virtual simulation and reappearance of PL processes, the integration and interaction between virtual and real world, as well as expandable carrier.

1. **Data-Model fusion-driven.** The term “data” refers to PLDTs data (physical/virtual/service data etc.), “model” refers to the PLDTs model covering multiple dimensions (geometric/behavior/rules, etc.), domains (mechanical/electric/hydraulic/control, etc.) and physical properties (material mechanics/structural mechanics/ theoretical mechanics, etc.), as defined by Tao et al. [39,156]. PLDTs data provides the data basis for online simulation and virtual-real synchronization of PLDTs model, and PLDTs model provides a carrier for data analysis and fusion of DTs data, which complement each other. Through the data-model joint drive, it has provided optimization functions for PL processes, such as online simulation, 3D visualization real-time monitoring, evaluation, prediction, control and decision-making [1].
2. **Virtual simulation and reappearance of PL processes.** Based on the DTs models for specific PLAs, virtual simulations of existing methods or schemes can be performed in the PLDTs system to verify and evaluate their feasibility, such as current management strategies of PLS, proposed methods or frameworks, new PLE operation strategies, etc. [75]. This process can be repeated without considering the cost of trial and error [35]. It is also able to apply the iteratively validated methods and strategies to physical space PL scenarios through virtual-real interaction [49]. The transformation of theoretical analysis to practical application has been achieved. Additionally, based on the historical operation data stored in the database, the process and state of historical PLAs can be reproduced, historical faults and abnormal problems can be traced [39,88]. These enable better identification and analysis of problems in PL.
3. **The integration and interaction between virtual and real world.** PLDTs has integrated the whole process, elements and services of PL in the virtual space, and connected the phases corresponding to the physical space through DTs data [108]. Therefore, the application of PLDTs can better achieve the integration and interaction of the physical and virtual worlds [1]. It is well positioned to address the challenges of the increasing digitalization and virtualization of PL processes management.
4. **Expandable Carrier.** According to Table s 2–6, the development of PLDTs system is closely related to other smart technologies, such as IoT, CPS, and CC [10]. Moreover, PLDTs system has the ability to integrate various intelligent technologies, and this integration results in highly functional systems with great potential for further development and facilitates the online upgrade of PLS [61].

5.2. Challenges

As shown in Fig. 9, the items in Table s 2 to 6 under “Applications” are categorized and counted according to factory environment, laboratory environment, case descriptions, and theoretical research. It can be seen that 50% of the samples underwent viability testing and validation in actual PL scenarios in factories. 20% of the studies constructed experimental platforms or designed simulation experiments for validation in a laboratory environment. 18% of the samples were supported by case studies, while 12% only expounded on relevant theories and concepts. It is evident that there are relatively few cases where PLDTs have been deployed in industrial scenarios, indicating that significant challenges still exist.

1. **PLDTs system integration is difficult.** Due to the interconnectedness of the various stages of PL, problems in any single step can significantly affect the overall efficiency of PLS. Previous research and industrial implementations of PLDTs have mostly focused on specific phases of PLAs, such as material allocation [110], PLE path planning [68] and warehouse management [95]. However, a comprehensive study and application of PLDTs system that cover all shop-floor activities of PL (including logistics activities during production, transportation, and warehousing) has not been addressed yet.
2. **Production and logistics synchronization face new bottlenecks.** Although the introduction of DTs facilitates effective production and logistics integration, it can lead to asynchronous characteristics of the virtual and physical worlds when random events occur in such a complex PLDTs system. This can lead to challenges in the physical synchronization of information, spatial-temporal synchronization and data-driven decision-making synchronization for the PLDTs system [20].
3. **Pay less attention to PLE health management.** Given its importance in PL, the breakdown of PLE can cause significant and irreversible economic losses by leading to the halt of all PLAs related to it. It is evident from Fig. 5 that relatively less attention has been paid to PLE health management in the existing literature. Researchers are more focused on PLE path planning, tracking, and localization instead.
4. **Construction of PLDTs lacks standards.** There is no unified standard for the construction of PLDTs, which has led to the varying roles and values of PLDTs in industrial applications [129]. Moreover, the construction of PLDTs requires a team of experienced engineers and multidisciplinary technicians for support [125].
5. **Construction costs may be high.** Affected by the scale of the shopfloor production line, in the early-stage PLDTs system, pursuing high levels of accuracy and completeness in PLDTs modeling may not be justifiable initially [114]. Furthermore, deploying high-precision sensors for real-time acquisition of PL data can significantly increase the acquisition cost [61,105].

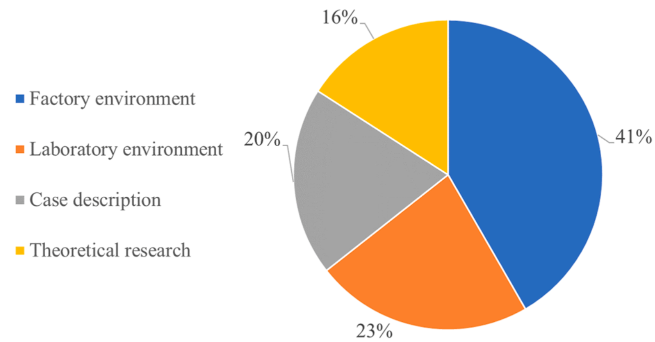

Fig. 9. Statistical sample validation method (132 papers: 2017–2022).

6. Future directions

Based on the challenges faced by PLDTs in industrial applications, research directions for PLDTs are discussed, taking into account the existing application scenarios, functions, and related intelligent technologies of PLDTs.

1. **Focusing on the construction methods of the PLDTs.** Existing modeling approaches mostly rely on statistical algorithms to transform data into representations of the physical process or system. However, these models are not interpretable enough to provide a deep understanding of the underlying mechanism [157]. It is not applicable to the construction of PLDTs models with multi-system integration, multi-physical property fusion, and the presence of a large number of interconnected intelligent PLE. Focusing on the problem of how to build DTs model, Tao et al. [158] established a

theoretical system for DTs model construction, and further carried out a theoretical study on the maturity evaluation of DTs model [159]. Zhang et al. [160] constructed a supply chain digital transformation maturity model based on the DTs. Wang et al. [161] proposed a DTs model construction method for smart manufacturing. However, for most enterprises, the real application of DTs requires more innovative exploration by researchers. How to fuse the high accuracy sensory data of PL processes with the complex operation mechanism to obtain the DTs model with high fidelity that can be applied. More efforts from scholars and practitioners are still needed.

2. **Focusing on multi-technology integration.** The literature review shows that technologies such as IoT, CC, and CPS serve as enabling technologies for PLDTs. They are not only the basis for realizing the bidirectional interaction of models and key data in each phase of PLDTs system, but also for achieving efficient collaboration between PL data sources and all phases of the PL lifecycle. Therefore, it is necessary to further investigate the efficient integration methods of DTs with multiple technologies to better characterize PLDTs system.
3. **Developing a full-process PLDTs system.** Affected by the operation mode and complex environment, systematically monitoring and evaluating the overall real-time operating state of PLS has become a long-term challenge for researchers and practitioners [5]. To address this challenge, research is needed on the whole-process intelligent system of PLDTs, which covers activities such as resource planning, transportation management, and intelligent warehousing. Using DTs data to drive PLS in real-time can enable the monitoring, upgrading, and transformation of PL processes. This presents an opportunity for the further development of PL, especially for practitioners.
4. **Working on the synchronization optimization of PLDTs based on transportation activities.** DTs is not only a useful tool for PLS integration, but also a powerful tool for establishing PL synchronization mechanism [72]. Due to the inevitable dynamics of the different layers (equipment level, line level and shop-floor) and multiple attributes (time, location, impact area, etc.) during PL operation. Transportation as a cross-cutting activity in the whole PL processes is the basis and key to the coordinated operation of PLS under dynamic disturbances [35]. Studying on adaptive synchronous decision-making of PL transport processes driven by DTs under stochastic conditions has been done in [5,35]. Meanwhile, solving the problems of physical synchronization of information, spatial-temporal synchronization and data-driven decision-making synchronization caused by dynamic perturbations in the operation of PLDTs system with a focus on transportation activities [10,20]. Thus, it may become a good potential for further research.
5. **Focusing on health management of PLE driven by digital-analog integration.** The PLE is the essential link between all stages of PL processes, and its healthy operation and timely maintenance are the prerequisites for the proper operation of PLS [162]. Although Pan et al. [5] and Bai et al. [70] have considered health management of PLE within the study of PLDTs, further efforts are needed. Since the PLE is gradually becoming larger, diversified and integrated, and is vulnerable to variable environment, variable load and variable operating conditions. Thus, PLE may face the following problems during service: (i) The performance degradation characteristics of critical components are difficult to detect. (ii) The collected condition data is non-ideal [163]. The literature review has shown that DTs provides an opportunity to solve problems with unknown mechanism or non-ideal data. Through iterative simulation of set failure conditions by DTs model, simulation data close to real system performance can be generated [164,165]. It can also fuse the performance degradation mechanism, generate data and perceptual data to solve the problems of difficulty in obtaining fault data and marking performance degradation features in traditional methods [166]. Therefore, how to build a “data-mechanism” fusion-driven PLE health management system to best support PLDTs. This may become an important potential for future research.
6. **Defining the role of government.** Considering the cost of planning and implementing DTs in PL, government legislation should actively pay attention to industry trends and strengthen publicity, encouragement, and support. Additionally, future directions for researchers in the field of PLDTs could involve standardizing PLDTs and encouraging global optimization and control based on DTs. Legislative measures, standardization efforts, and governmental support are even more crucial in the PL field, which is inherently vulnerable to information and communication technology upgrades and improvements.

7. Conclusion

This paper presents a comprehensive overview of DTs’ application in PL. The discussion begins with a detailed analysis of the latest research on PLDTs, followed by an exploration of the diverse functions played by DTs within various PLAs. Furthermore, the application of DTs in each PLAs is discussed in detail, from the perspective of transportation, packaging, warehousing, material distribution and information processing. And the roles played by intelligent technologies such as IoT in PLDTs system are summarized. The advantages, challenges and future research directions of PLDTs are also discussed. In conclusion, DTs provides a new perspective on intelligent operations in PL, enabling online simulation and real-time monitoring, virtual design and planning, positioning and tracking, evaluation and forecasting, as well as decision synchronization. Nevertheless, there still exists a need for more comprehensive theoretical research and industrial practice by researchers and practitioners alike. This article aims to explore the specific application scenarios and functions of DTs in PL, offering an appropriate classification and broad suggestions briefly. We hope that the discussion will promote the innovative development of PLDTs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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