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Research Article

Application of Digital Twins to Flexible Production Management: Taking a Shandong Factory as an Example

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In recent years, digital twin technology has greatly promoted business development at both digitization and networking levels and has received widespread attention. However, DT technology still has problems such as real-time data interaction, component integration, and restoration of reality. This paper proposes a framework that combines DT with 3D visualization techniques to address these issues. Taking the intelligent logistics management 3D scheduling system of a factory in Shandong as an example, the applicability of digital twin to flexible production management is verified.

1. Introduction

Since Michael Grieves initially proposed the DT (digital twin) concept in 2002, academics have defined DT from many perspectives [1]. In general, DT has more added value and can serve many areas owing to the background of the IoT (Internet of Things), big data, and Industry 4.0 [2, 3]. The DT allows for real-time transparency of critical logistical data by combining the virtual and physical worlds [4, 5]. Second, by monitoring the production process and analyzing data in real time, a DT can help create efficient production management, other than just simulation [6–8]. Furthermore, early simulation is not only costly but also time-consuming in terms of equipment debugging and postmaintenance [9]. In these two aspects, however, DTs outperform early simulations [10]. Therefore, digital twin technology plays an important role in the whole process of product life cycle [11, 12].

DT technology has played a role in promoting the digital transformation [13] of the manufacturing [14], health care [15, 16], and education [17]. For this reason, DT has become the center of attention in industry and academia in recent years [18, 19]. Furthermore, the investment cycle in DTs will reduce by 30% in the next several years [20]. Several large companies, such as General Electric, Siemens, PTC, Dassault Systèmes, and Tesla, are applying DT to improve product performance, manufacturing, production management flexibility, and competitiveness [21]. DTs are quickly becoming an essential aspect of digital transformation, and their potential impact is enormous [22]. Therefore, the application research of digital twin is of practical significance.

In recent academic research, DT technology applies to virtual testing, production control, process optimization, and equipment maintenance in the engineering industry [23]. However, only 18% of studies have data transfer in both directions [24]. That is because DTs will have some challenges in practical applications as follows: (1) The rate of information exchange in real time is low [25, 26]; (2) high integration of models, systems, and data [27, 28]); and (3) the simulation's degree of realism is low [29]. In addition, the lack of a digital twin framework is also one of the reasons why it is difficult to implement [30]. Due to the above reasons, the specific applications of digital twins in various industries are limited. Therefore, it is imminent to study the specific application of digital twin.

This study summarizes the demand features of DTs and describes their current state of research. The composition framework, development model, and core technology of DTs are proposed based on the features of DTs. Among them, the combination of DT and VR technology plays a key role in system virtual debugging and later equipment maintenance [31]. In order to verify the feasibility of the framework, we take the logistics management 3D scheduling and monitoring system of a factory in Shandong as an example.

There are five parts to the article. The next part discusses the current state of research on the topic of this article. The third section covers the framework's design, including development concepts, core technologies, and a software overview. The fourth section offers a case study that demonstrates DTs how to improve production management, and examines the case study's results and lessons gained. Finally, a summary of this study is presented, as well as future research directions.

2. Background

In recent years, the use of VR (virtual reality) and DTs has covered a wide range of engineering fields, including design, production, manufacturing, and maintenance [32, 33]. In practical applications, the information transfer between the virtual system and the real world, the degree of real restoration, and the product life cycle are mainly considered. Generally speaking, maximizing the use of DT technology can increase the productivity of a business while reducing losses due to downtime or equipment failure. Therefore, the advantages of DT provide great help for enterprises to carry out digital transformation.

2.1. Flexible Production Management. DTs are an indispensable technology for realizing intelligent factories [34]. But the most frequent function of all DT practices is maintenance. Through DT, equipment life prediction can be performed, and high-precision 3D models can be used for remote maintenance guidance to achieve highly flexible management [35]. To overcome the problem of long simulation time in the past, Abdelmegid et al. [37] proposed a framework that combines simulation modeling practice with the Last Planner VR system to bridge this gap.

A petrochemical plant implements intelligent production control based on DT technology [37], and a product assembly workshop implements flexible production and management based on DTs [38]. These two studies both reflect the application of DTs in flexible production and management. However, such practical application research is relatively rare, and most of the other research types are still in the theoretical research stage [39]. The research of this paper not only proposes a new construction framework but also proposes practical application cases. We supplement practical cases for this research.

2.2. Digital Twin. The study of DT starts with a concept and then realizes a specific function according to its characteristics [40]. The importance of DT for businesses is to increase the added value of products at every step of their life cycle [41]. The DT expands the previous simulation model and can carry out the simulation operation of the authentic system [42]. However, there are also some challenges, such as how to synchronize virtual and actual production systems [43]? Also, how can real-time data and the command be sent and received between the two platforms? The research in this paper proposes a new solution to this problem [44].

To synchronize with the authentic production system, Talkhestani et al. [45] recommended that the data of the virtual simulation model be updated using the anchor point approach. The intelligent manufacturing workshop that drives the panels in parallel can solve the online intelligent transmission of manufacturing resource data between the two systems [46]. In terms of built framework, for example, the research on the implementation framework of DT in the welding production line [47].

The above research is to optimize the application of DT in the factory from a specific angle, such as data synchronization and model optimization. The purpose of this paper is also the same as the above research, which aims to propose new solutions to the challenges encountered in the application of digital twins. This study builds the framework of the DT based on the real demands of the enterprise and the basic concept of the DT, drawing on the benefits of the previous research.

2.3. 3D Visualization and Virtual Reality. The development and testing of physical devices have become the key barrier for successful production as product complexity has increased and product life cycles have shrunk. Using "virtual prototype" technology in the design process to eliminate hardware testing and iteratively enhance physical prototypes, on the other hand, will save businesses a significant amount of money and time [48]. High-precision simulation based on the construction of sophisticated 3D physical models, on the other hand, is highly costly in terms of computation and time, severely limiting its use [49], before production equipment, virtual simulation, and testing possible with DT and 3D visualization [50], that is, through virtual manufacturing and visual monitoring of the manufacturing process, which improves the product design environment and reduces development costs.

VR is applied in a variety of sectors to provide tangible and significant advantages such as urban planning, real estate marketing, architectural design, and others. VR will play a key role in product design and development, as well as quality production management because it can reduce the design cycle, boost project completion quality, and lower investment and development expenses. This study establishes a DT framework by combining VR and 3D visualization technologies for DTs to better boost company production management.

3. Build a Framework

The DT's framework refers to a specific DT hierarchical structure, information required for modeling, and modeling methods [51]. Framework facilitates the design, optimization, and control of human-machine cooperation throughout the product development process [52, 53], allowing users to create and execute DTs [54]. The system structure, information synchronization, models, and how to merge these parts into a framework must consider while constructing a DT [55]. To this, reduced-order modeling is trustworthy enough for predicting DTs while yet allowing for rapid evaluation [56]. Second, the PLC (programmable logic controller) system collects data from the assembly system and then synchronizes with the virtual model in the DT through the open platform communication server [57]. This section will introduce the DT's development model, core technologies, and framework.

3.1. Design Features. This article synthesizes many perspectives on the characteristics of DTs and summarizes its key features, such as the simultaneous operation of virtual and actual production systems, rapid information gathering, and system integration [58, 59]. This paper divides the role of digital twin into manufacturing stage and service stage.

3.1.1. Manufacturing Stage. The utilization of digital twins in the product production stage can reduce product introduction time and boost product delivery speed. It may increase product quality, optimize processes, and lower product manufacturing costs in production management. We create a virtual manufacturing line using digital twin technologies to track all material production and circulation processes. The following three points are the vital roles of the virtual system in the product production stage:

(1) Product design and virtual commissioning: virtual commissioning of physical equipment and software systems during equipment manufacture can decrease the debug's error and accelerate the project timeline. Product design in virtual systems can help to accelerate the introduction of new goods while also lowering the cost of product design.

(2) Digital production line: using DT for information like materials and equipment throughout the manufacturing process. Simultaneously, it collects numerous data from the manufacturing process to offer a foundation for future analysis and optimization.

(3) Process capability evaluation and vital indicator monitoring: we collect real-time operational data from different production equipment on the production line of the whole manufacturing process to provide a visual monitor. To ensure the normal functioning of the manufacturing process, we set KPI monitoring policies and vital device parameters. Furthermore, analyzing the information gathered may optimize operations to improve product quality and productivity.

3.1.2. Service Stage. Many enterprises now utilize large sensors to gather data and apply data analysis to avert production failures, enhancing product quality, thanks to the maturation of IoT technology and the drop in sensor costs. The digital twin at the service stage helps the enterprise's flexibility management in the following two areas:

(1) Remote monitoring and equipment maintenance: for instance, visible remote control of virtual systems may help businesses save labor expenses and personnel aggregation. Second, you may develop a monitoring system for device health indicators using data acquired by the authentic scene. Artificial intelligence and machine learning allow for the prediction of equipment usage, assist the management of maintenance and replacement parts, and reduce losses caused by unscheduled outages.

(2) Enhance production efficiency: equipment makers may construct experience models for numerous application situations and manufacturing processes to improve product quality and production efficiency by accumulating a large amount of production data.

3.2. System Design. This section will introduce the basic steps of building a DT, including development models, key technologies, and system frameworks.

3.2.1. Development Model. This section is to compare the development model of DTs with classical simulation. As seen in Figure 1, an engineering project frequently necessitates engineering design first, followed by a wait for manufacturing equipment. After installing the physical equipment, debugging is required to confirm the equipment's regular operation. In general, waiting for equipment manufacture integration and installation might take up to two months. Previously, 3D modeling lacked a solid model, but DT's 3D modeling now has one, allowing for a proportion of 1 : 1 restoration of the actual world. Given this, using DT can debug the equipment in advance in the virtual world, hence shortening the project's building duration. The most crucial point is that the previous simulations include a lot of repeated work, which will result in a lot of unnecessary expenditures. However, the DT development model may run many programs at the same time, saving time. Simultaneously, virtual debugging equipment can lower the cost of debugging. As a result, DT's product development model may save time and money than the typical simulated linear development strategy.

3.2.2. How to Build a DT? Figure 2 shows that the framework of the DT. All the work is mainly divided into three stages: early stage, middle stage, and later stage. The early stages mostly need study and data gathering. We combine client demands and data to create a systematic design strategy that will serve as the foundation for future modeling and software development. The data gathering process includes the integration and analysis of product production data and equipment operating data. The main goal of the midterm task is to create models in the virtual world using manual data and to present the realistic environment in a 1 : 1 ratio for 3D modeling. The model in the virtual world

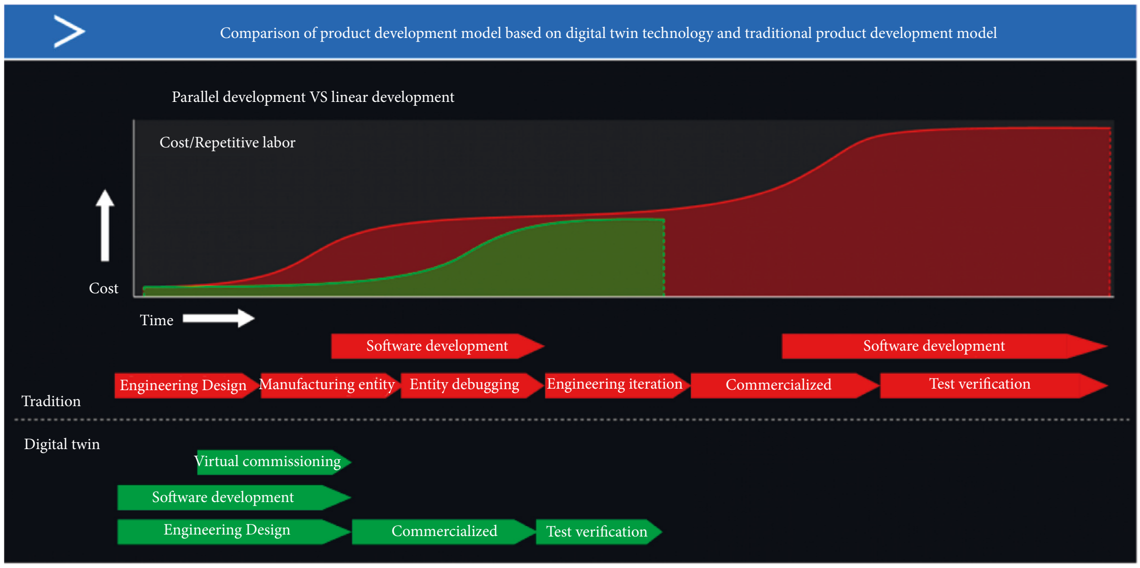


Figure 1: To compare the development models.

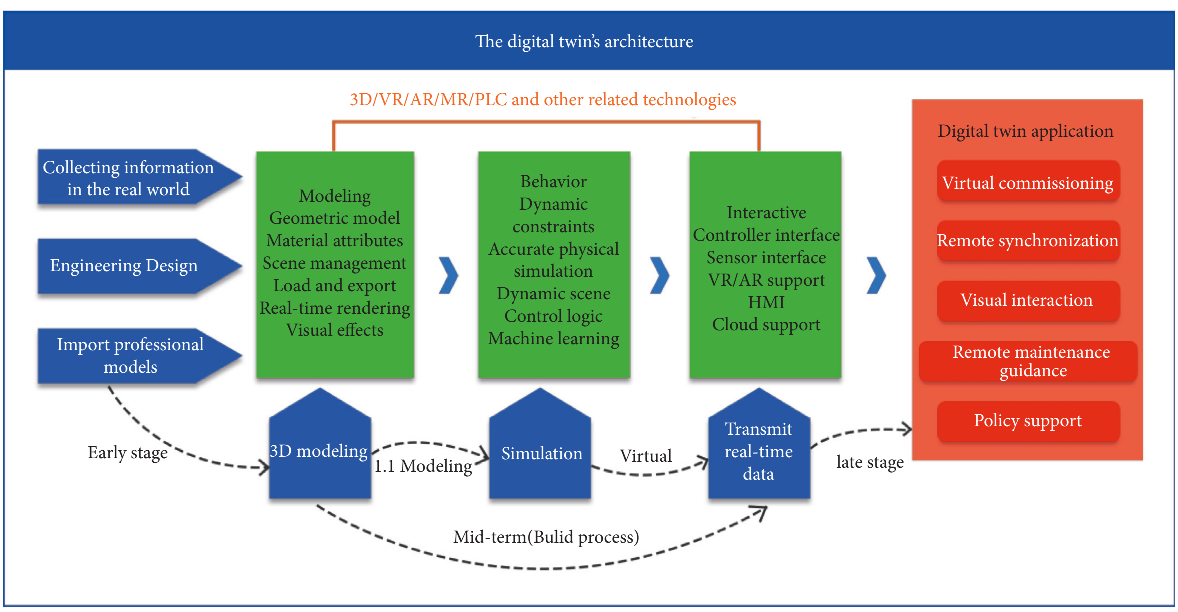


Figure 2: The digital twin's structure.

requires the visual effect to be close to reality, and the model's material must be consistent with actuality in terms of data. It lays the foundation for enterprises in the management of equipment use. Finally, based on the previous, the system simulation operation is carried out through the virtual scene made by the model. Here, by writing abundant data codes to achieve dynamic constraints to ensure the operation and dynamical display of the entire system, we include physical equipment debugging and software system debugging. After debugging the whole system, it can be installed and used directly in real life.

In general, the construction of a DT is mainly composed of four steps: collecting data, modeling, debugging, and installation and joint debugging. The real system is synced with the virtual system once it deploys by collecting data from different sensors and transferring data from the server. Data are transferred in real time between them. The complete system may be executed in a virtual scenario using PLC interface technology, allowing for remote synchronization. Remote synchronization will serve the enterprise's production management and equipment auxiliary maintenance. The phases and functions listed above cover the complete enterprise's production and operating cycle. It may oversee and service the whole business process, assisting the company in increasing operational efficiency and improving its automated management capabilities.

4. Case Study

This article utilizes a project in Shandong as an example to demonstrate the framework's applicability. The purpose is to construct a set of intelligent logistics management 3D scheduling monitoring systems for a plant in Shandong using DTs. Figure 3 shows the project's execution processes, including eight routines, which are demand analysis, system design, 3D modeling and software design, system simulation, virtual debugging, system installation, and project acceptance. The existing scheduling interface can display all production processes and no more blind spots. Users can intuitively monitor all areas with this monitoring system, which entirely replaces the old monitoring system. This project has improved the flexibility of business production management after applying this monitoring system. The project includes a production area, storage area, and sorting area, with a 396-day building timeframe. After testing, the firm has successfully accepted it.

4.1. Survey of Demand. We investigate and evaluate the enterprise's management needs to develop project goals. The purpose is to gather production equipment operating data over the Industrial Internet and employ DT technology to accomplish equipment digitalization and 3D visualization based on the demands of businesses. Therefore, the goal of the project is to design a monitoring and scheduling system for the enterprise, to achieve effective on-site and remote equipment operation and maintenance management solutions while improving manufacturing quality.

4.2. Intelligent Logistics Management Software Design for a 3D Dispatch Control System. The system is the creation of a logistics management system using DT technology. Software design and 3D modeling are going together simultaneously, and they are then debugged jointly in the virtual system. This section will introduce the software components and functionalities used in this system.

The monitoring system is set to WMS (warehouse management system), VRWCS (virtual reality warehouse control system), INF (Device INFormation File), and VRMTS (virtual reality model test system). Figure 4 shows the interrelationship between types of software. Although the software is connected, there are still levels, and the WMS system belongs to the top-level scheduling system. VRWCS is a WCS that simulates reality, and it directly controls the various independent devices at the bottom. The INF docks with information systems of the enterprise to ensure the synchronization and docking of information.

4.3. System Development. System development includes creating a three-dimensional model in the virtual environment and debugging equipment and software systems. We program the established 3D model and debug the virtual physical equipment. Simultaneously, we debug the software system, eliminate any issues, and optimize it until it is ready to be put in the firm.

4.3.1. 3D Modeling. In the past, simulation modeling required engineering design first, followed by modeling. 3D modeling may be done directly according to the scenario with the new 3D modeling software, saving a lot of time than

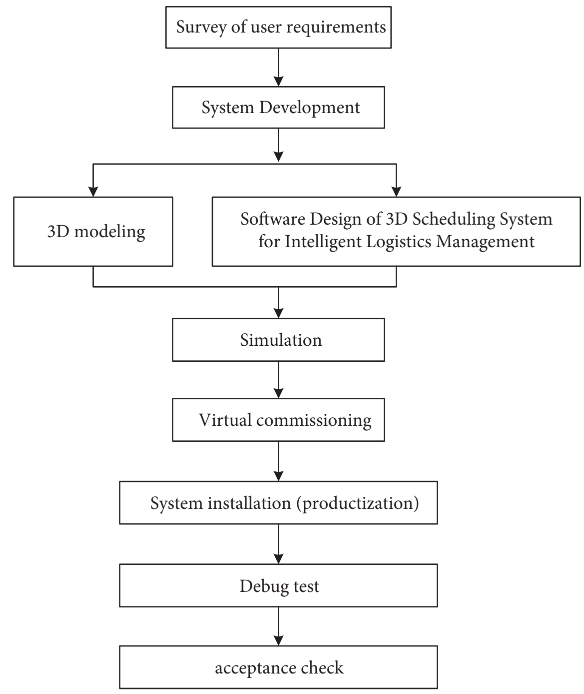


Figure 3: Case implementation steps.

before modeling. "Zhongwushi" is the modeling and simulation software utilized in this study (the design software is shown in Figure 5). The difference between the DT's 3D modeling and earlier simulation modeling is that the previous simulation modeling lacks a model, making it impossible to troubleshoot. Figure 6 depicts a device model in the DT's three-dimensional modeling. The logistics equipment in the virtual system and the actual equipment have a 1 : 1 correspondence. The 3D scene modeling should base on the authentic scenario, and the size, look, and other aspects of the logistical equipment should correspond to the actual circumstances.

4.3.2. Debugging. After finishing the 3D modeling, we can create code for the complete model, so it can run. Virtual debugging entails both the installation of hardware and the scheduling management of the software system. The software system scheduling control is to load the entire intended software system into the hardware equipment in the virtual scene and test the software system to determine whether there will be any difficulties with the system. Testing in a virtual system helps detect and address problems in advance, reducing debugging time. After debugging is complete, the software can implement in reality.

Furthermore, in order to complete accurate analysis and optimization, all dynamic information of products in the circulation process needs to be collected. However, these needs rely on expensive physical measuring gear such as sensors, acquisition systems, detecting systems, and so on. However, this will limit the extent of measurement coverage and result in the loss of monitoring for many indicators that cannot be collected directly. DT technology can leverage machine learning to infer data that cannot be directly

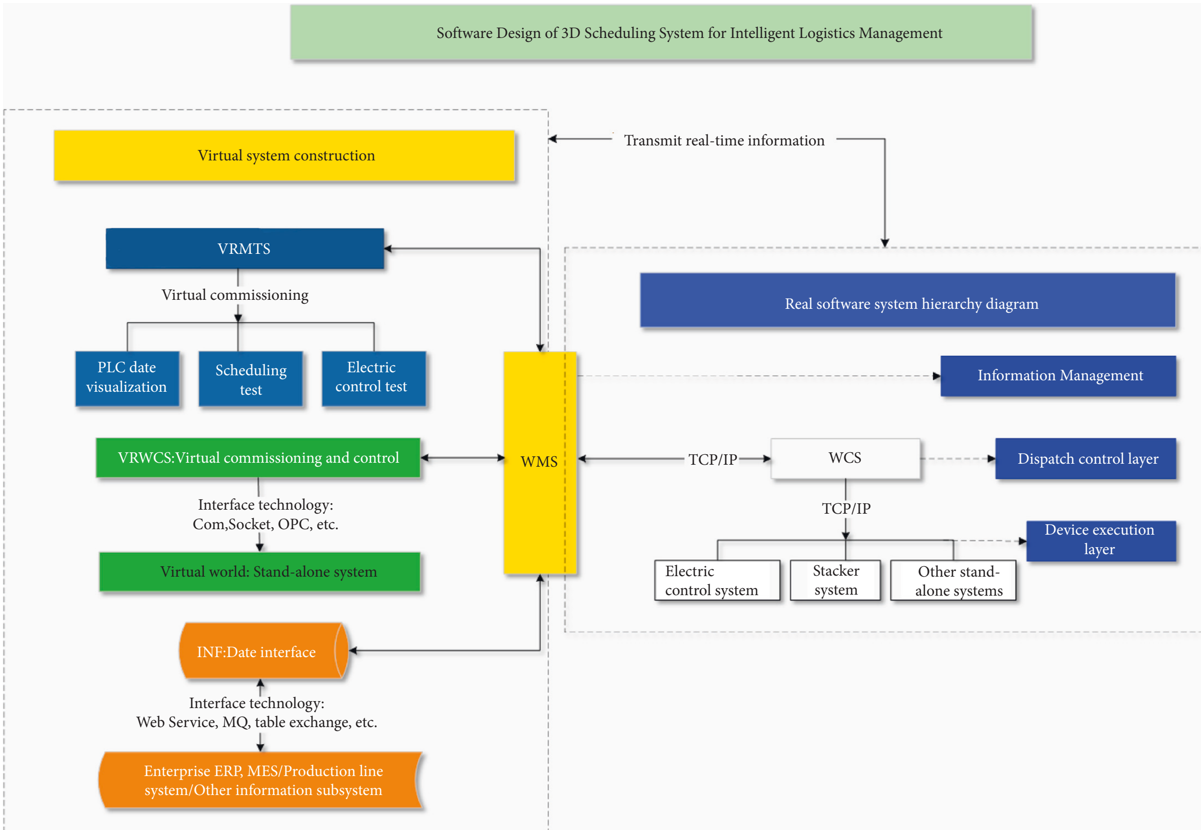


Figure 4: Design an intelligent logistics management 3D dispatch system.

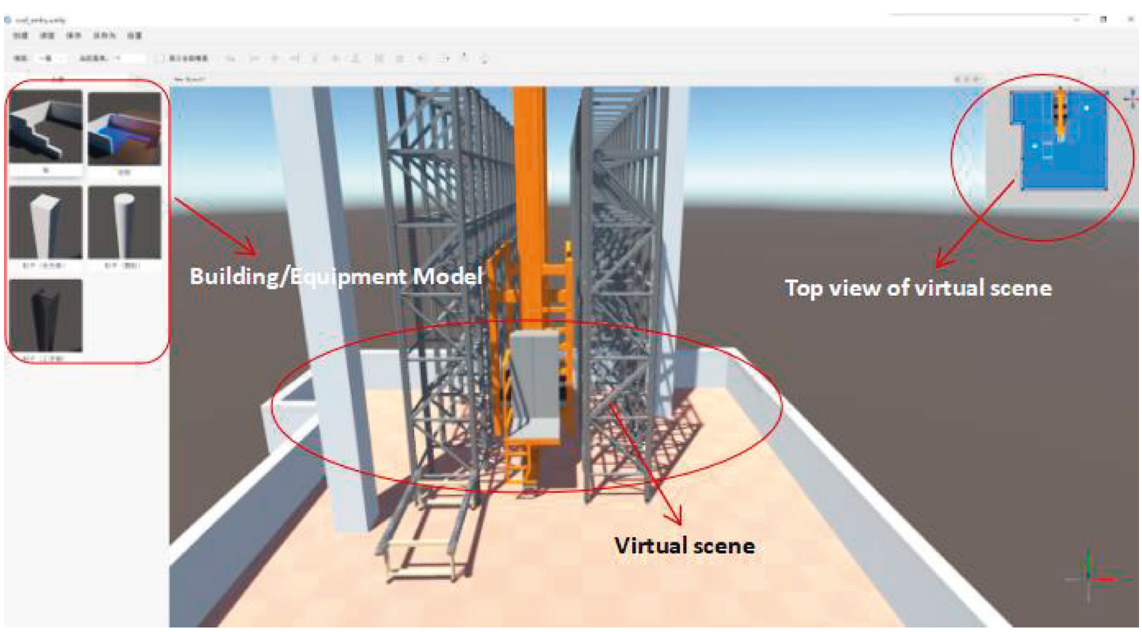
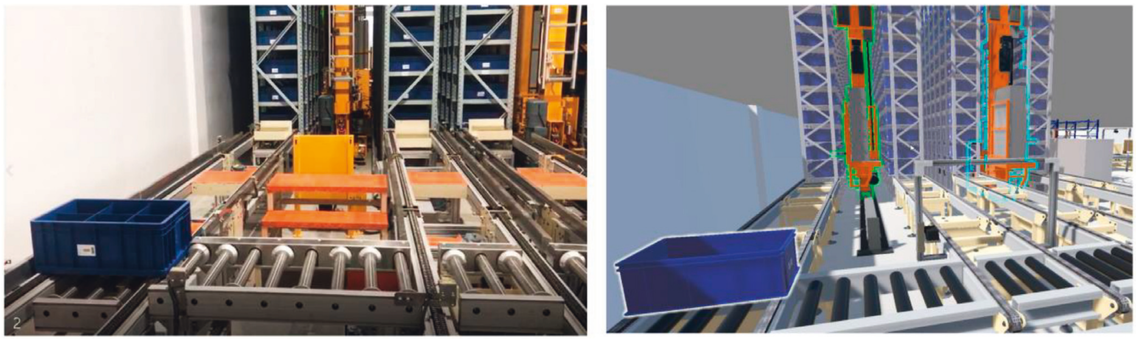


Figure 5: Virtual scene design software.

monitored and captured, saving organizations money on equipment.

In the case study of this article, a total of 8 different types of bugs appeared during debugging (Table 1 shows these bugs). Compared with the prior on-site debugging volume, discovering using digital twin technology for virtual debugging has reduced debugging faults by 70%.

4.4. Installation of the System. After the installation is complete, the information should sync between virtual with real world, and the different information interfaces and systems may be synchronized and docked. The 3D scheduling monitoring technology enables managers to watch the whole production and operating process immediately.



Real scene Virtual scene

Figure 6: Compare the actual and virtual scenes.

Table 1: Show the issues that arose throughout the debugging process.

Serial number	Problems in case debugging
1	The program is not working.
2	The software system's assignment is erroneous, resulting in a disordered program
3	The platform equipment's height is improper, and the stacker cannot take up the products.
4	The motor's rotational direction is incorrect and cannot transport the material.
5	The material could not be transported from station A to station B because the signal transmission between the two stations failed.
6	Poor power contact of a motor causes the conveyor to be unstable.
7	The frequency of wireless transmission is wrong, and the signal transmission fails.
8	A disturbed scheduler leads to inefficient equipment.

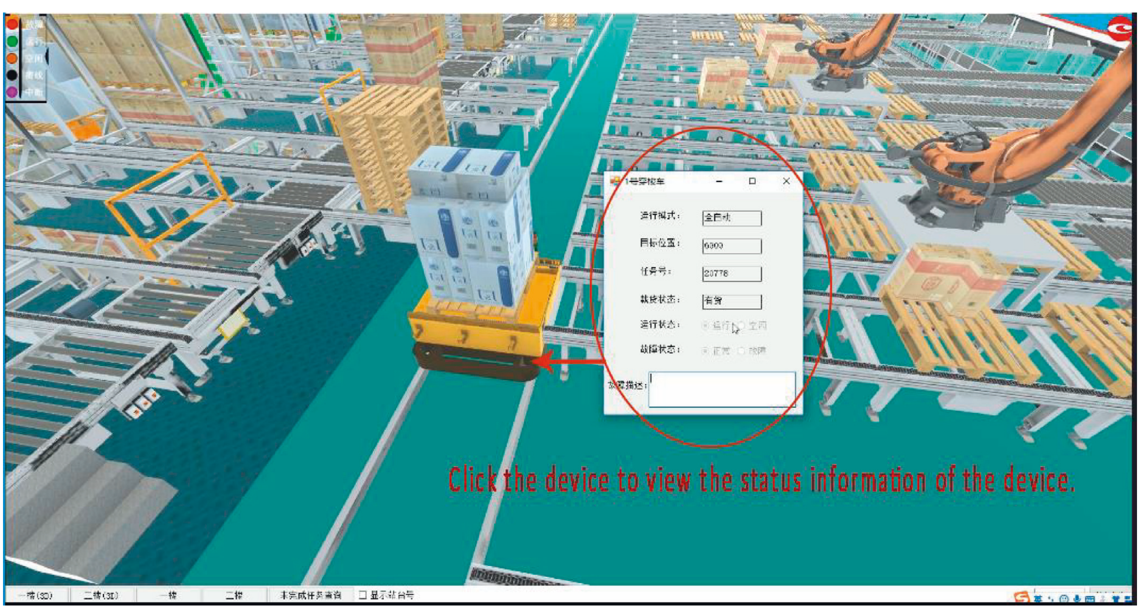


Figure 7: Demonstrate the 3D dispatch monitoring system's Kanban feature.

The following are the results of the intelligent logistics management 3D dispatching monitoring system:

First, we employ holographic effects to display goods or equipment that function as a virtual digital display. Users may view the operational status of different equipment (such as stackers, conveyors, robots, shuttles, and so forth) via the monitoring screen (as shown in Figure 7). In terms of visual sense, the system supports a maximum of 20,000 data collecting points and a maximum of 75 frames per second throughout all operations.

Second, as shown in Figure 8, when you click on a moving cargo, all the detailed information of the cargo will be displayed next to the cargo, such as material brand, quantity, and stack type. In the monitoring interface, operators can view all material information intuitively, which is helpful for inventory count.

Figure 8: Cargo area view.

Furthermore, it offers organizations a VR scene system with a feeling of immersion identical to the actual logistics scenario. After donning the VR helmet, the manager may freely traverse the virtual scene and learn about the project's actual logistical operation procedure. The VR helmet renders at a rate of at least 75 frames per second. The primary role of VR helmets is to teach new employees, assist new employees in understanding the production condition, provide off-site advice during equipment maintenance, and assist enterprises in quickly resolving equipment failure problems, resuming production, and reducing losses.

4.5. Practical Application Comparison. This section will discuss the effectiveness of DTs in boosting corporate flexibility management. Simultaneously, we compare the findings of this study to current research on DTs in manufacturing and application. Finally, we discuss the issues of DTs in flexible production management.

This project primarily increases the flexibility of corporate production management in the following areas. First of all, virtual debugging based on DT technology has reduced debugging faults by 70%. Second, the system addresses the production enterprise's low equipment maintenance efficiency and high maintenance expenses. When production line equipment fails, it may minimize failure recovery time, enhance production efficiency, reduce operating costs, reduce the needs on the ability of on-site maintenance people, and efficiently handle equipment maintenance pain points. Finally, using the Industrial Internet's remote maintenance guidance technology and comparing the number and cost of the firm's prior staff, it has been discovered that the system can save the company 40% of labor costs. In addition, remote equipment maintenance instruction can save equipment makers around 50% in trip costs. It can swiftly adapt to the enterprise's demands and improve the enterprise's production management flexibility. Most importantly, the system may effectively reduce staff travel and gathering during the epidemic time while assuring production work development.

Furthermore, when the equipment is running, the system will gather status information, allowing operation workers to remotely and intuitively grasp the working state of the equipment. The fault system may automatically send problem information to the mobile phones of operation and maintenance workers to ensure regular production. According to the example's scene error data, the error between the large scene and the virtual system is within 1 second, and the error of the small scene is within 200 milliseconds, which basically realizes the complete synchronization of the two systems.

Table 2 compares this paper's digital twin framework with other studies. As can be seen, the advantage of digital twin technology lies in what kind of specific application environment it is combined with. Compared with Ma et al. [60], the main difference lies in the product life cycle. This study and Cimino et al. [61] are based on practice solutions to the challenges of digital twin technology. But the focus of this study is on the synchronized operation and information transfer between the two systems to improve business management. Cunbo Z and Leng J are primarily a bias toward studies done on specific factories for DTs. The framework provided in this article is more comprehensive and does not constrain the industry.

Finally, finding some issues with DTs is throughout the project's execution. According to research, while machine learning opens up numerous possibilities for DTs, some circumstances will be limiting their applicability. The low degree of automation and informatization of businesses, for example, will make it impossible for DTs to acquire fundamental data. The services available in other phases will not be constrained if the DT does not need to execute

Table 2: A comparison of digital twins applied research.

Author	Contribution	Effect	Contribution of this article
Ma J, Chen H, Zhang Y, et al.	To address how to create a digital twin-driven production management system for product life cycle management	The faulty product rate and work-in-process inventory were decreased by 34% and 89%, respectively, while the product's first-time inspection pass rate climbed by 14.2 percent	The case's debugging bugs were decreased by 70%, and the operation and maintenance employees were cut by 40%
Cimino C, Negri E, Fumagalli L	At the Politecnico di Milano's School of Management to implement DT in a laboratory equipped with MES	Create applications that provide the groundwork for addressing the questions in the literature	Create a digital twin architecture to enable synchronized operation of virtual and physical systems
Cunbo Z, Liu J, Xiong H	A framework of intelligent production management and control techniques for sophisticated product assembly workshops is proposed based on digital twins	More specific	Propose a framework for the composition of digital twins (extensive, not restrictive to the industry)
Leng J, Zhang H, Yan D, et al.	The authors apply DT at a laboratory equipped with MES at the Politecnico di Milano's Management School		

simultaneously with the authentic system. For example, in the research and development stage of many products or equipment, digital twins can exist independently without data docking with real systems.

5. Discussion and Conclusion

DT generates functions such as disassembly, check, transfer, modification, and deletion by transforming many features of physical equipment into virtual space. The application scope of DT is gradually expanding, and how to use this technology to improve services has become a hot research topic at present. However, DT faces the challenges of real-time data transmission and true restoration in practical applications. Aiming at these problems, this paper proposes a solution that combines DT technology and 3D visualization technology. And we proved its feasibility through a practical application case of a factory in Shandong. The results show that DT technology is of great significance for improving the flexible production management of enterprises.

In terms of theory, the research in this paper proposes solutions to the challenges encountered by DT in practical applications. That is to say, it is proposed for the real-time information transmission and true reduction problems of DT found in previous studies, which is a supplement to the research in the field of DT. In terms of practical significance, the first is to promote the practical application of DT. Secondly, it brings practical and objective flexible management to enterprises, reduces labor costs for enterprises, and, at the same time, avoids the restriction that people cannot gather due to the new crown epidemic. The two powerful advantages of simulation and cost reduction make the research of DT technology further expand. According to the current development status, the future research direction must be toward the digital twin supply chain. Research on digital supply chain will enhance the holistic and systematic nature of enterprises, and future research will also enrich this field [34].

Data Availability

The data used to support the findings of this study are currently under embargo, while the research findings are commercialized. Requests for data, [6/12 months] after publication of this article, will be considered by the corresponding author.

Conflicts of Interest

The authors have no relevant financial or nonfinancial conflicts of interest to disclose.

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