Abstract: The integration and application of a warehouse system and manufacturing system has become a manufacturing problem for enterprises. The main reason is that the information control system based on automation and stereo warehouse is inconsistent with the production and management information system of the enterprise in terms of business, data, functions, etc. Based on this, this paper studies the implementation of an automated warehouse based on the integration of ERP (enterprise resource planning) and WMS (warehouse management system) with the method and technology of the intermediate table. Moreover, MES (manufacturing execution system) is the brain and the core part of a sustainable digital factory. The enterprise adopts advanced intelligent and information technology to build and deploy the MES, realize fine management and agile production, and meet the personalized needs of the market. Therefore, this paper studies the implementation path and effect based on MES from an industrial realization to construct a sustainable digital factory. The research results of this paper can improve industrial efficiency and reduce costs for enterprises in storage capacity, handling capacity, response rate, rate of error, number of operators, etc.

Keywords: sustainable digital factory; automated warehouse; WMS; ERP; smart manufacturing

1. Introduction

With the changes in the global market, the manufacturing industry in major industrial countries is facing new challenges [1]. The trend of manufacturing transformation is imminent, and countries have put forward their own plans. Germany advocates the industry 4.0 plan [2], while China officially released the made in China 2025 plan in May 2015 [3], aiming at improving the innovation ability of the national manufacturing industry and promoting the deep integration of industrialization and informatization [4]. Among them, “Smart Manufacturing Engineering” mentioned: “relying on advantageous enterprises, closely follow the intellectualization of key processes, robot substitution of key posts, intelligent optimization control of production process and supply chain optimization, and build digital factories & digital workshops in key fields [5]”.

1.1. Research Background

The automated warehouse is an important part of the rapid development of modern logistics system [6]. It has many advantages, such as saving land, reducing labor intensity, eliminating errors, improving the level of warehouse automation and management, improving the quality of management and operators, reducing storage and transportation losses, effectively reducing the backlog of working capital, and improving logistics efficiency [7,8]. The automated warehouse, which is connected to the plant-level computer management information system and the production line, is an essential key link between CIMS (computer-integrated manufacturing system) and FMS (flexible manufacturing system) [9,10].

A variety of hardware equipment and software products of the automation system can be developed around the automated warehouse, such as different types of inventory
management software, system simulation software, graphic monitoring, and scheduling software, stacker conveyor control software, barcode identification and tracking system, handling robot, stacker manipulator, automatic trolley, cargo sorting system, stacker address detection system, stacker control system, cargo location detector, height detector, conveying system, stacking system, automatic conveying trolley and other products [11–13].

The struggle to move to just-in-time (JIT) delivery requires distribution centers to readapt to this reality, and a mathematical programming approach is proposed, based on a min–max formulation that returns the optimized layout of a cross-docking warehouse that feeds a just-in-time distribution operation [14]. In order to meet the just-in-time systems, a mathematical model and a JIT parts feeding system are presented [15].

MES (manufacturing execution system) is an indispensable intermediate bridge for sustainable digital factories to realize information integration [16], and it can provide users with a fast response, flexible and refined manufacturing environment [17]. It also can help enterprises reduce costs, deliver goods on time, and improve product quality and service quality [18,19]. MES is not only an essential part of building a sustainable digital factory but also one of the most effective means of building a sustainable digital factory [20]. More and more manufacturing industries pay attention to and gradually use MES to enhance the core competitiveness of enterprises [21].

1.2. Existing Problems

The sustainable digital factory is the future development trend of manufacturing factories. A sustainable digital factory is composed of basic hardware equipment, intelligent equipment, and a management software manufacturing system [22]. It needs to integrate Internet of Things technology, intelligent sensor technology, industrial wireless sensor network technology, heterogeneous intelligent integration technology of international development fieldbus and control network, intelligent processing, and other technologies into all links of production [23–26]. In China, many manufacturing enterprises still have many problems in carrying out the construction of digital factories. For example, there are still a large number of isolated islands of automation and information, the management gap between the planning layer and the control layer, and the actual situation of the workshop cannot be accurately and timely fed back to the relevant personnel of production management [27]. Therefore, the construction of MES is very important for manufacturing enterprises. MES is the core of the sustainable digital factory production system, which connects the upper planning management system and the lower automatic control system. The core task of the information management system for the workshop execution layer of manufacturing enterprises is to release all kinds of information and instructions from the planning layer to the specific production line or other types of work centers [28]. It can collect and analyze production data in real time, monitor the production status [29], quickly respond to workshop feedback [30], ensure on-time delivery, and improve production efficiency and product quality [31].

The research on the construction of sustainable digital factories is focused on the concept and value of the sustainable digital factory [22], as well as the main contents and precautions of sustainable digital factory construction. However, there is still a lack of research on how to build a sustainable digital factory based on MES, especially from the aspects of framework construction, implementation path, index evaluation, etc.

1.3. Research Motivation and Organization Structure

In the process of connection between the enterprise production management system and the warehouse management system, there are problems such as the independence of operating systems, the inconsistency of interfaces, the inability to unify standardized management in business, and the differential control of equipment and facilities. Therefore, this paper studies the integration and application of ERP (enterprise resource planning) and WMS (warehouse management system). This paper is a further extension of a conference paper [32] based on the construction of the sustainable digital factory.
Moreover, this paper mainly establishes a sustainable digital factory from the perspective of a top-level framework, system model, and industrial implementation. The original idea of this paper is mainly embodied in two aspects: an automated warehouse based on the integration of ERP and WMS, and the construction of a sustainable digital factory based on MES from an industrial realization. The unique contribution of this paper is as follows: through information integration with other application systems, enterprises can improve production efficiency, strengthen information management, shorten the product production cycle, and reduce manufacturing costs. Finally, by constructing the enterprise’s sustainable digital factory, the enterprise’s market competitiveness is also can be improved.

The organization structure of this paper is as follows: (1) Introduction, (2) Overall Architecture of Sustainable Digital Factory, (3) The integration of ERP and WMS for Automated Warehouse, (4) Industrial Realization, (5) Implementation Effect, (6) Case Study, and (7) Conclusions.

2. Overall Architecture of Sustainable Digital Factory

Combined with the MES functional model and the characteristics of the sustainable digital factory, according to the four-tier structure of enterprise integration, this paper puts forward the overall architecture of the sustainable digital factory based on MES, as shown in Figure 1. The architecture diagram is divided into four layers: equipment layer, interaction layer, MES layer, and enterprise layer.

![Overall architecture of MES based sustainable digital factory.](image)

**Figure 1.** Overall architecture of MES based sustainable digital factory.

2.1. Enterprise Layer

The enterprise layer includes ERP, OA (office automation), CRM (customer relationship management), SCM (supply chain management), PDM (product data management), visual Kanban, and war situation center. CRM user orders are transferred to ERP to make production plans [33–35]. At the same time, through the OA system, SCM, material order...
management, R&D (research and development), PDM, and other auxiliary support, the production plan is transferred to the MES level of the factory. The MES layer collects factory data to reflect the current production situation of the factory. The ERP layer shall complete the order according to the MES feedback. The manufacturing plan can be adjusted by product quality inspection reports, material consumption in the production process and various production performance reports. This can more reasonably arrange manufacturing resources, improve production efficiency and reduce manufacturing costs. The essence of MES-based sustainable digital factory architecture is that the factory uses production data analysis to obtain operation knowledge, so as to realize real-time and dynamic optimization of the sustainable digital factory and improve the level of intelligent manufacturing.

The information systems of the enterprise layer include ERP, OA, CRM, war center, visualization bulletin board, SCM, PDM, etc.

2.2. Workshop Layer

The middle core layer is the intelligent manufacturing execution layer. It interfaces the upper and lower layers of the service set layer through a specific port and communicates with a certain protocol. It includes four modules: planning and scheduling management, quality management, workshop resource management, and statistical analysis management. Planning and scheduling management module: process scheduling, intelligent dispatch, production tracking, and material management. The quality management module includes product tracking, inspection management, quality traceability, and basic data. The workshop resource management module includes personnel management, equipment management, tooling management, and data collection. The statistical analysis management module includes plan statistics, man-hour statistics, personnel statistics, and document analysis. According to the relevant information obtained from data statistical analysis, combined with real-time early warnings such as data workshop modeling and data visualization tools, feedback control and optimization simulation are carried out, and planning and scheduling management optimization, production quality optimization, and production workshop resource management optimization are completed. Thus, the purpose of production process management such as intelligent production diagnosis and intelligent production decision-making can be achieved.

The MES layer includes four modules: planning and dispatching management, quality assurance, workshop resource management, and statistical analysis management [36]. Among them, the planning and dispatching management module includes working procedure, dispatch, intelligence, dispatch, process, track, material, and administration. The quality assurance module includes product track, test administration, quality traceback, and basic data. The workshop resource management module includes personnel administration, equipment administration, work clothes administration, and data collection. The statistical analysis management module includes plan statistics, quality statistics, working hours statistics, and file analysis.

2.3. Control Layer

This layer is the interaction with basic equipment, mainly including the connection and integration of communication equipment such as DNC (distributed numerical control), switch, wireless network, RFID (radio frequency identification), and configuration of various sensors [37,38]. By collecting multi-source data in the manufacturing process, data exchange and communication are carried out according to a certain communication protocol. Then, the equipment layer is controlled and managed through a data acquisition system and production monitoring system, so as to achieve the mutual inductance interconnection of manufacturing production resources in a sustainable digital factory [39]. It also includes some data workshop modeling and data visualization tools [40].

The main functions of the interaction layer include digital workshop modeling and data visualization tool [41]. The supported information systems and tools include PLC (pro-
grammable logic controller), DNC, data acquisition, monitoring system, switch, wireless network, RFID, etc.

2.4. Equipment Layer

This layer is the supporting layer of MES, including automation equipment and other data acquisition equipment, mainly including physical manufacturing resources such as industrial robots, intelligent machine tools, acquisition cards, scanning guns, AGV (automated guided vehicle) carts, and sensors.

The equipment layer mainly includes all kinds of equipment in the workshop, such as logistics equipment, processing equipment, assembly equipment, welding equipment, storage equipment, etc.

3. The Integration of ERP and WMS for Automated Warehouse

In automatic warehousing, enterprise resource management systems and warehousing management systems are very important. The resource connection, information integration, data exchange, function, and business collaboration and integration between the two are the key points of this paper.

3.1. ERP and WMS for Automated Warehouse

The ERP (enterprise resource planning) is an enterprise resource management system that integrates enterprise management concepts, business processes, basic data, human and material resources, computer hardware and software. Its main purpose is to comprehensively balance and optimize the management of the comprehensive resources owned by the enterprise, such as people, money, materials, customers, information, time and space, coordinate various management departments inside and outside the enterprise, carry out business activities around the market orientation, and improve the core competitiveness of the enterprise, so as to obtain the best economic benefits [42,43].

The WMS (warehouse management system) is an important part of warehouse management. It uses warehouse management software to conduct warehouse in/out, warehouse transfer and allocation, inventory, disassembly/assembly review and other operations to ensure the safety, integrity and first in first out principle of material storage [44]. The automated warehouse is shown in Figure 2 [32].
3.2. Functional Integration

The functional connection and integration of ERP and WMS are shown in Figure 3 [32]. Among them, the two ends are the functional modules of ERP and WMS, and the middle is the bridge between them, namely the data and communication module. Through this function integration, the coordination and unification of the enterprise production management function and warehouse management function can be realized.

![Figure 3. The functional integration of ERP and WMS for automated warehouse.](image)

3.3. Business Integration

The business process of ERP and WMS connection is shown in Figure 4 [32]. ERP business includes completing the receipt and delivery in the ERP system, completing the warehouse in and out instruction in the ERP system, ERP records inventory in WMS, etc. The business integration between ERP and WMS is realized through the intermediate table and the intermediate interface.

![Figure 4. The business integration of ERP and WMS for automated warehouse.](image)
3.4. Data Integration

The system architecture of ERP and WMS data integration is shown in Figure 5 [32]. WMS data mainly includes inbound and outbound reservations (DB) and operation performance (DB). ERP data mainly includes receipt/issue order (DB) and receipt/issue order.

![Figure 5. The data integration of ERP and WMS for automated warehouse.](image)

In addition to ERP and WMS, the information system providing data management and control also includes ECM (engine control module), WCS (warehouse control system), AGV (automated guided vehicle) system [45], RCS (robot control system), etc.

4. Industrial Realization

The following will build a sustainable digital factory from the perspective of MES, as shown in Figure 6. The implementation path of the following four parts gradually improves the various capacity systems of the sustainable digital factory, including the management and control capacity of the transparent traceability system of production data, the management, and control system of production data, and the intelligent operation system of production.

![Figure 6. Implementation path of MES-based sustainable digital factory.](image)
4.1. Transparent Traceability System of Production Data

Digital factories should build production transparency capabilities. The MES system can monitor the workshop equipment and production status in real-time. ISO (international organization for standardization) reports and charts can visually reflect the current or past processing status. In this way, enterprises can know the status of intelligent production equipment and process information at a glance. In terms of function and implementation, it is mainly implemented from the following aspects:

- Basic production data management (product number, process, equipment, personnel, etc.) [46];
- Production work order management (creation, splitting, deletion, automatic or auxiliary dispatch, etc.) [47];
- Equipment management (status, capacity load data, equipment operation data, etc.) [48];
- Production task management (commencement preparation, report management, etc.);
- Work report barcode or RFID technology solution;
- Production process quality management;
- Production progress data query and visual Kanban management.

4.2. Production Data Management and Control System

A real-time, effective, and interactive production data management and control system can help enterprises realize the effective management of manufacturing plants. At the same time, it is also a breakthrough for manufacturing enterprises to build digital and intelligent chemical plants. After the transparent and traceable construction and improvement of production data, it is necessary to further improve the control ability of production data and build it from the aspects of personnel, equipment, materials, quality, and Andon, as follows:

- Personnel capability matrix management, work skill control;
- Equipment networking, production process operation parameter control;
- Material error proofing control (product number, batch, and quantity);
- Quality data control [49];
- Andon early warning management system.

4.3. Production Intelligent Operation System

The purpose of producing an intelligent operation system is to realize the transparency and tracking of production data to control of production data. Adopt advanced sensing technology, data mining, and optimization technology, and classify, sort, and analyze massive data through a large platform. At the same time, various algorithms are established to optimize the model and provide the optimal and real-time professional production intelligent operation scheme. The following is to build an intelligent production operation system from the aspects of intelligent dispatch, scheduling, material distribution, control, and intelligent production regulation [50]:

- Intelligent dispatch of production batch tasks to equipment and production line;
- Intelligent scheduling of production resources (equipment and personnel);
- Automatic material calling, replenishment, and intelligent material distribution;
- Process quality intelligent control;
- Intelligent adjustment of production parameters.

4.4. Sustainable Digital Factory Based on Intelligent Manufacturing

By copying the previous workshop’s intelligent operation system to other workshops, the intelligent integration of all workshops in the whole plant is realized [51]. Use the Internet of Things technology and monitoring technology to strengthen information management services, so as to improve the controllability of the production process, reduce manual intervention in the production line, and reasonably plan and schedule. At the same time, by integrating intelligent emerging technologies and intelligent systems, build
a humanized sustainable digital factory with high efficiency, energy saving, green, environmental protection, and comfort. Finally, cooperate with relevant enterprises upstream and downstream of the industrial chain to promote intelligent manufacturing.

5. Implementation Effect

The above is to build a sustainable digital factory from MES based on the above four steps. The expected benefits generated by the implementation of the system in the sustainable digital factory are shown in Figure 7.

Figure 7. Expected benefits of implementation.
5.1. The First Stage

The visualization of equipment load, production progress, quality and quantity, Kanban, etc., is realized through the implementation of a data transparency system [52]. Finally, the efficiency of plan execution, order-receiving ability, rapid response, quality analysis, and personnel work can be improved. The corresponding indicators are as follows:

- Reduce management complexity (including standardization of site management, management mode replicable) [53];
- Reasonable management of granularity (including traceability of production process, improvement of plan execution efficiency, improvement of plan enforceability);
- Field equipment load transparency (including OEE, overall equipment efficiency) [54];
- On-site task progress transparency (including improvement of the ability of quick order receiving, quick response ability of documentary);
- Transparency of site quality data (including improvement of quality analysis ability);
- All staff visualization (including improvement of staff efficiency).

5.2. The Second Stage

Through the implementation of a production data management and control system, equipment OEE, product yield, and knowledge inheritance ability are improved. The corresponding indicators are as follows:

1) Improvement of personnel efficiency
   - Reasonable distribution of personnel skills;
   - Reasonable use of personnel skills.

2) Improvement of equipment efficiency OEE
   - The equipment responds quickly to abnormal conditions and reduces the waiting time for unreasonable production tasks;
   - Equipment status is reflected in real time, production tasks are quickly scheduled, suggestions are made to reduce downtime, and reasonable personnel performance evaluation.

3) Improvement of product yield
   - Eliminate the bad products produced by unqualified skills;
   - Eliminate production defects caused by wrong materials;
   - Eliminate the after-sales cost caused by the outflow of defective products.

4) Improvement of quick response ability

5) Improvement of the ability of knowledge inheritance

5.3. The Third Stage

Through the implementation of the production intelligent operation system, the commencement, completion, and material completion rate of the work order are improved. At the same time, it can reduce in-process inventory, in-process defect rate, and production cycle. Improve manufacturing execution (delivery capacity) by optimizing the enterprise’s production management mode and strengthening process control. By establishing a standardized production management information platform, the information between the internal field control layer and the management layer of the enterprise can be interconnected [14]. Finally, enterprises can grasp information changes in time, on time, and in real time, and on demand, so as to improve the management mechanism and ability of enterprises and improve the core competitiveness of enterprises. The corresponding indicators are as follows:

- Improvement of on-time operation rate;
- Improvement of on-time completion rate;
- Improvement of the start-up and completion rate;
- Improvement of in-process inventory;
- Reduction of the defect rate in process;
- Reduction of production cycle.
6. Case Study

The above analyses of the construction of a digital factory are based on automated warehousing from the perspective of the overall framework, theory, industrial practice, etc. The following will analyze and verify the research theory with a practical case.

6.1. Case Background

KAINENG HEALTH company, founded in 2001, is a high-tech enterprise specializing in home water treatment improvement, technology R&D, and product manufacturing. It is a pilot enterprise of the integration system of the Ministry of Industry and Information Technology. As the first residential water treatment company in China to put forward the concept of whole-house water purification and family health, its products are exported to home and abroad. The construction of the company’s sustainable digital factory started in 2003.

At present, the company has improved the key technical equipment such as the full-automatic production line of the FRP barrel, the intelligent assembly line of the control valve body, and the intelligent RO membrane element processing system. At the same time, it has built intelligent manufacturing standards and information security systems and improved the workshop sensing and control network. It built a network connecting ERP, MES, PLM, SCM, and CRM OA. Other core business systems are integrated into an intelligent enterprise operation platform to build a healthy sustainable digital factory of water purification and household appliances.

6.2. Construction of Sustainable Digital Factory

This case analyzes the overall architecture of the sustainable digital factory proposed in Section 2, mainly covering four levels, namely, the enterprise layer (Section 2.1), workshop layer (Section 2.2), control layer (Section 2.3), and equipment layer (Section 2.4).

In the enterprise layer, case studies mainly include enterprise production management, enterprise collaborative management, collaborative supply chain management based on order life cycle, and support information systems. At the workshop layer, case studies mainly include digital design, automatic machining, robot assembly, intelligent detection, automatic production line, and supporting information systems. In the control layer, case studies mainly include precision manufacturing stability and reliability technology, deformation inspection and control technology, internal manufacturing Internet of things, the connection between factory and group network, and network interconnection with external cooperative units. In the equipment layer, case studies mainly include automatic measurement vision robots, robot-assisted assembly, tightness detection robots, robot deburring and chamfering systems, automatic bending equipment, robot stacking system, and welding robot.

6.2.1. Enterprise Layer

At the enterprise level, enterprises build digital chemical plants from the aspects of production management, collaborative management, and collaborative supply chain management based on the order life cycle.

Enterprise Production Management

Enterprise resource planning management: shorten the turnover time through the implementation of the intelligent product life cycle management system based on an ERP system. It can realize the integration of logistics and capital flow and strengthen material and production planning. It can simulate the impact of different market conditions on production planning, capacity demand planning, material procurement planning, storage, transportation, etc. It can enhance the rapid response ability of enterprises to changes in the business environment. It can realize the management’s real-time and online queries for information. It can provide more accurate and timely financial reports for enterprise decision-making. It can provide various management reports and analyze data in time.
Product life cycle management: strengthen product development management and improve engineering BOM (bill of material) through a product development life cycle management system. Firstly, the digital product library of water purifiers is established. By building a reasonable data architecture and optimizing information flow parameters, we can improve data reusability and interface compatibility. Using high-speed information interconnection technology, various systems in the whole process of product design, process, manufacturing, and inspection of water purifiers such as CAD (computer-aided design), CAE (computer-aided engineering), CAPP (computer-aided process planning), CAM (computer-aided manufacture), PDM (product data management) are connected to realize the integration, sharing and scientific management of information flow. Finally, the full digital design of water purifier products is realized, so as to achieve the digital management of the whole life cycle.

Enterprise Collaborative Management

Enterprise collaboration management includes project management collaboration, procurement management collaboration, production management collaboration, quality management collaboration, logistics management collaboration, and warehouse management collaboration.

Project management collaboration: system integration through the PS module of the SAP (system applications and products) system. In the PS module, the plan management, cost management, expense management, and other information data control of the whole project are realized. The collaborative management of project progress is achieved by applying the functions of the project plan, project budget, capacity plan, resource management, and result analysis in the PS module.

Procurement management collaboration: it deeply applies the SAP system and SRM system. The SAP system controls the data of purchase requisition, purchase quantity, purchase price, and purchase order from the system level. The SRM system enables enterprises to establish long-term and close business relations with suppliers. Through the integration of resources and competitive advantages of both sides to jointly explore the market, expand market demand and share, reduce the high cost of products in the early stage, and realize a win–win enterprise management mode. The SRM system closely integrates advanced e-commerce, data mining, collaborative technology, and other information technologies, and provides an optimized solution for the strategic design of enterprise products, strategic acquisition of resources, effective negotiation of contracts, unified management of product content, and other processes.

Production management collaboration: achieve the collaboration and integration of manufacturing management and production planning through the efficient application of the MES system. Through the application of the MES system, the in-depth integration of the workshop execution layer for manufacturing enterprises is achieved. MES system is integrated into management modules provided by enterprises, including manufacturing data management, planning, and scheduling management, production scheduling management, inventory management, production process control, and so on. It can better coordinate manufacturing management and production system effectively.

Quality management collaboration: combined with SAP’s QM (quality management) system to control the quality of this material supply chain. It plays an important role in monitoring products from raw material procurement to product delivery. It is also integrated with other modules to form the monitoring of the whole process system of products from raw material procurement to manufacturing to shipment. It includes incoming inspection (outsourcing), WIP (work in progress) inspection, final process inspection, and shipment inspection. It avoids data inconsistency and reduces the error of repeated entry of relevant data. Finally, it completes the coordination between the production plan and quality management to ensure that the quality of produced products meets the requirements.

Logistics management collaboration: use bar code technology to realize the interaction between material status information and the ERP system. Improve the management
strategy of materials on and off the shelf through the bin management module. The wireless positioning and tracking of key materials are realized by using radio frequency technology (RFID). Adopt batch and serial number management to improve identification and traceability information management.

Warehouse management collaboration: the warehouse management module cooperates with LES (logistics execution system). Materials are managed from different aspects such as warehouse receipt, warehouse management, and material distribution through the LES system.

Collaborative Supply Chain Management Based on Order Life Cycle

Order collaboration: includes bid support, order preparation, order start, and order design. Through MM and PP modules, complete manufacturing BOM (MBOM) based on material technical status and improve project management. With the help of the project management module (PS), network operation information management is realized.

SRM supplier management system: SRM receives purchase orders created and synchronized from the SAP system. The purchase order is controlled by nodes through the order collaboration module, so as to realize the timely sharing of the order information and improve the ability of plan control and risk control in the purchase process. Order collaboration is mainly divided into five nodes to control the purchase process: (1) order receipt (the factory sends the order, and the supplier receives/rejects the order); (2) order confirmation (the factory makes a specific delivery plan, and the supplier confirms the delivery date and delivery quantity); (3) production progress (the supplier reports the production progress according to the configured production template. The system compares the actual completion progress with the production template, and tracks, monitors and reminds the production progress; (4) delivery collaboration (the supplier creates and sends the shipping notice, and the factory confirms after receiving the goods); (5) order settlement (the supplier creates an invoice and sends it to the factory. The factory reconciles the invoice information in the SRM system, pays in the SAP system, and provides the invoice payment information to the supplier in the SRM system for viewing).

Purchase collaboration: it includes the collaboration of supplier life cycle management, bidding demand fulfillment, and purchase receipt. Purchase materials are classified through the mm module to manage RFQ and quotation process, purchase order process, purchase contract process and plan agreement process. Information interaction with suppliers is realized through a supply chain management system (SCM). Supplier relationship information management is realized through a supplier management system (SRM).

Manufacturing collaboration: it includes the collaboration of manufacturing, packing, and shipping. Support material distribution management by completing component allocation in the ERP system. Through the establishment of a valuable production library, activity-based costing is realized. By improving the manufacturing management system (MES), dispatch information management is realized.

Service collaboration: it includes collaboration of installation service and after-sales service. Build full life cycle service management with 3G and EPC long-term cooperation service mode. The operating characteristics and customer requirements are identified by constructing the life cycle model of the water purifier. Combined with the factory’s innovative 3G technology, core business processes, and standardized management mode to build a menu and flexible full life cycle service mode.

Support Information System

The supporting information system includes an ERP system, PDM system, PLM system, QMS system, SCM system, SRM system, management information system, and water purifier remote diagnosis system.

ERP system: it is an enterprise information management system mainly for the integrated management of material resources, capital resources, and information resources in the manufacturing industry. ERP is enterprise management with management accounting
as the core and integrating real-time information. It is an integrated enterprise information management system for material resource management (logistics), human resource management (people flow), financial resource management (financial flow), and information resource management (information flow).

PDM/PLM system: it will be used after the SAP-PLM module is online. The functions of process approval and voucher storage are realized in SAP-PLM. All drawings and documents in the plant are created, changed, and approved in the PLM module, and the drawing vouchers, specification vouchers, and materials are associated with the SAP system. Finally, this information is output and transmitted through BOM to control product quality from the design source. It can realize “open source” and “generate money”, reduce direct costs, improve the R&D ability of enterprises, shorten the product life cycle, and then improve the core competitiveness of enterprises.

QMS system, i.e., quality management system: it plays an important role in monitoring products from raw material procurement to product delivery. It is also integrated with other modules (such as mm, PP, SD, and PM) to form the monitoring of the whole process system of products from raw material procurement to manufacturing to shipping. It includes incoming inspection (outsourcing), WIP inspection, final process inspection, and shipping inspection. It avoids data inconsistency and reduces the error of repeated entry of relevant data.

SCM system, namely supply chain management system: information interaction with suppliers is realized through the supply chain management system (SCM).

SRM system, i.e., supplier management system: supplier relationship information management is realized through a supplier management system (SRM).

Water purifier remote diagnosis system: make up for the deficiency of the existing water purifier group controller through the remote diagnosis system. Through the server connected to the Internet, the functions of monitoring, analysis, and diagnosis are realized. The remote diagnosis system provides the functions of fault diagnosis, potential fault diagnosis, and performance analysis. It also adds the functions of the historical operation data record, user authority management, maintenance supplier user management, and so on.

6.2.2. Workshop Layer

At the workshop level, enterprises from digital design, automatic processing, robot assembly, intelligent detection, and other aspects build a digital chemical plant. This section will study the implementation path based on MES from the workshop layer to construct a sustainable digital factory.

Digital Design

Serialization and modular design and development: evaluating the feasibility of the modular design of each set of parts. Through the construction of a three-dimensional process standard process of modular assembly parts, a series, modular and standardized three-dimensional process of typical assembly parts is formed.

Three-dimensional aided design: three-dimensional digitization for new product development. Through the gradual three-dimensional transformation of existing products to improve the single machine hardware configuration of designers. The first is to standardize and customize the interface, template, and parameters of 3D design software. The second is to formulate and improve various standards, specifications, and processes such as 3D design, verification, and data flow.

Three-dimensional virtual simulation: process three-dimensional simulation, combined with main products, complete the work related to process three-dimensional simulation and output files. Combined with the three-dimensional process of typical assembly parts, a standard three-dimensional process flow of modular assembly parts is formed.

User demand differentiated BOM: use ERP system to complete user orders and form differentiated BOM according to user needs.
Automatic Machining

Intelligent processing production line: study the stacking process, production beat and logistics to form an efficient automatic stacking production and manufacturing system. Improve the utilization efficiency of production resources by replacing manual operation.

Welding production line: solve the problems of difficult welding and poor welding environment. According to the characteristics of dissimilar metal welding structures, a robot welding system is developed. By studying the feasibility of robot welding and welding process parameters, the robot’s automatic welding of dissimilar metals is realized. In order to improve the welding environment of welders, improve the reliability of welding quality and reduce labor intensity.

Robot Assembly

Robot-assisted assembly: aiming at the sensitivity of coil insulation surface, a driving robot is developed to realize coil automatic mechanical assisted wire embedding. Studying the precision assembly method to reduce the risk of coil insulation damage improves the automation level, flexibility, and efficiency of the assembly process and reduces labor intensity.

Robot stacking: through the secondary development of an ordinary manipulator, the corresponding auxiliary device is developed to realize automatic stacking. It can not only reduce labor intensity and improve production efficiency but also reduce process dispersion and reduce quality risk.

Intelligent Detection

Automatic measurement: through the development of a complex cavity space operation (continuum) robot, which studies high-precision digital measurement methods, visual detection technology, and intelligent diagnosis methods. It can detect the internal operation status of products and the integrity of parts without rotor extraction. It can greatly reduce product maintenance costs and maintenance time and has considerable social and economic benefits.

Rapid three-dimensional detection of ring: according to the three-dimensional digital model of the product and the point cloud matching mathematical model, the end automatic forming equipment is adopted to improve the end forming quality and efficiency. At the same time, the online measurement process and coil detection are applied to measure the three-dimensional shape and size by developing the corresponding three-dimensional measuring device and supporting software.

Automatic Production Line

Digitize each station equipment and integrate it with the assembly line logistics system to realize the automation and intelligence of the manufacturing process, so as to improve the processing capacity range and processing efficiency of the equipment.

Supporting Information System

It includes an MES system, flexible manufacturing system, intelligent detection system, manufacturing intelligent information system, and operation intelligent monitoring system.

MES system: its modules include manufacturing data management, planning and scheduling management, production scheduling management, inventory management, quality management, human resource management, work center, equipment management, tool and tooling management, procurement management, cost management, project Kanban management, production process control, bottom data integration analysis, upper data integration decomposition, and other management modules.

A flexible manufacturing system (FMS) has compound processing capability. It can process many different types of products at the same time without reconstruction and maintain high production efficiency through high technology.
Intelligent detection system: it can accurately test the output power and load capacity of various equipment. It mainly tests all electrical parameters of the equipment, including dynamic parameters. It is composed of measurement and control and load cabinet. It is used with the upper computer to realize intelligence. It can automatically complete the special test of all electrical parameters of the generator set and generate charts, curves, and test reports at the same time.

Operation intelligent monitoring system: it is composed of a generator intelligent controller, wireless data collector, server, and monitoring center. The system is connected to the Internet by wireless transmission and can be monitored remotely and in real time. By monitoring the start and stop of equipment, power generation status, oil engine status, fuel status, mains power status, etc., the all-around maintenance management and power generation management of the generator set can be realized.

6.2.3. Control Layer

At the control level, enterprises build digital chemical plants by developing stability and reliability technologies, inspection, and control technologies.

Precision Manufacturing Stability and Reliability Technology

The production process is simulated by numerical simulation technology to intuitively and quantitatively analyze the machining process. Through the research of deformation prediction and surface positioning error calculation, the possible machining defects are predicted and corrected.

Deformation Inspection and Control Technology

Through non-contact measurement technology, precision detection at low speed is realized. The machining accuracy is ensured by studying the deformation mechanism in the process of material removal and the influence law of process parameters on the deformation size.

Internal Manufacturing Internet of Things

It relies on manufacturing an Internet of Things system, running a remote detection platform, running centralized control system, and manufacturing an information platform. Interconnected from the equipment layer, control layer, workshop layer, enterprise layer, and other levels to connect the laboratories in the enterprise. The laboratory includes a metal materials and welding laboratory, mechanical vibration and modal laboratory, insulation laboratory, and other laboratories in the enterprise.

Interconnection between Factory and Group Network

It relies on the group’s internal network and the group’s intelligent control platform. Through the interconnection between the equipment and the group’s intelligent monitoring platform, the data in the factory can be transmitted to the group’s intelligent monitoring platform.

Network Interconnection with External Cooperative Units

It relies on the external Internet of the enterprise. Interconnection with external partners through the Internet to realize the interconnection of raw material suppliers, generator customers, scientific research institutions, universities, external laboratories, and cooperative enterprises.

6.2.4. Equipment Layer

The equipment layer includes an automatic measurement vision robot, on-site detection special robot, a robot-assisted assembly, a tightness detection robot, a robot deburring and chamfering system, automatic bending equipment, a welding robot, etc.
Automatic Measurement Vision Robot

By developing a complex cavity space operation (continuum) robot, high-precision digital measurement, visual detection, and intelligent diagnosis can be realized, which can detect the internal operation status of the equipment and the integrity of parts.

Field Detection Special Robot

According to the characteristics of complex deep cavity structure, a complex cavity space operation (continuum) robot is developed.

Robot-Assisted Assembly

Aiming at the sensitivity of coil insulation surface, a driving robot is developed. It can improve the automation level, flexibility, and efficiency of the assembly process and reduce labor intensity.

Tightness Detection Robot

Through the secondary development of an ordinary manipulator, the corresponding auxiliary device is developed to realize automatic stacking.

Robot Deburring and Chamfering System

The robot will automatically perform the roughening, chamfering, grinding, and cleaning of each machining surface according to the processed three-dimensional model. It can greatly reduce labor intensity and improve the quality of depilation and cleaning.

Automatic Bending Equipment

It can not only save a lot of tooling design and manufacturing costs but also overcome the large dispersion of the manual bending process. Through the input of the three-dimensional model and point cloud matching mathematical model, the automatic forming of the end is realized. At the same time, rapid measurement, detection, and control are realized by developing corresponding three-dimensional rapid measurement devices and supporting software.

Robot Stacking System

Through the secondary development of an ordinary manipulator, the corresponding auxiliary device is developed to realize automatic stacking. It can not only reduce labor intensity and improve production efficiency but also reduce process dispersion and reduce quality risk.

Welding Robot

Through the development of a robot welding system, the robot automatic welding of dissimilar metals is realized, the welding environment of welders is improved, the welding quality and reliability are improved, and the labor intensity is reduced.

6.3. Implementation Effect of Construction of Sustainable Digital Factory

According to the survey and statistics of many foreign MES users conducted by the American MES Standards Association, the successful implementation of the MES system will greatly improve and improve in many aspects. The average benefits of the successful implementation of MES are shown in Table 1.

It can be seen from the above table data that the improvement of these data can bring considerable time and economic benefits to enterprises. However, from the perspective of manufacturing enterprises that have successfully implemented MES in China, MES has also brought many value-added services and the improvement of production creativity to enterprises.

The company began to build a sustainable digital factory by implementing the MES system two years ago. The statistical analysis of the questionnaire survey of users in each
workshop and relevant departments is shown in Figure 8. The overall average value of several indicators has been greatly improved after the application of the MES system. The production balance is 28% higher than before. Meanwhile, the in-process inventory decreased by 25% and the non-performing rate decreased by 33%. This can make enterprise management more information-based, transparent, and intelligent. The MES system not only has a positive impact on the group company locally but also improves the core competitiveness of the enterprise as a whole and fundamentally.

Table 1. Average benefits of successful MES implementation.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Project</th>
<th>Average Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First Survey</td>
</tr>
<tr>
<td>1</td>
<td>Shorten product manufacturing cycle</td>
<td>45%</td>
</tr>
<tr>
<td>2</td>
<td>Reduce or eliminate data entry time</td>
<td>75%</td>
</tr>
<tr>
<td>3</td>
<td>Reduce WIP quantity</td>
<td>17%</td>
</tr>
<tr>
<td>4</td>
<td>Reduce or eliminate job conversion work</td>
<td>56%</td>
</tr>
<tr>
<td>5</td>
<td>Shorten product lead time</td>
<td>32%</td>
</tr>
<tr>
<td>6</td>
<td>Improve product quality (reduce defective products)</td>
<td>15%</td>
</tr>
<tr>
<td>7</td>
<td>Loss elimination instrument/blueprint</td>
<td>57%</td>
</tr>
</tbody>
</table>

Figure 8. Main indicators after implementation.

6.4. Implementation Effect of Integration of ERP and WMS for Automated Warehouse

Table 2 shows the comparison between the industrial benefits generated by this research method and the traditional warehouse. On-site physical objects based on integration and docking of ERP and WMS are shown in Figure 9 [32].

Table 2. Implementation effect.

<table>
<thead>
<tr>
<th>Category</th>
<th>Unit</th>
<th>Traditional Warehousing</th>
<th>Warehouse Integrating ERP and WMS</th>
<th>Rem Arks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage capacity</td>
<td>Warehouse number</td>
<td>3000</td>
<td>11,000</td>
<td>Under the same area</td>
</tr>
<tr>
<td>Handling capacity</td>
<td>20 containers</td>
<td>6</td>
<td>20</td>
<td>12 h</td>
</tr>
<tr>
<td>Response rate</td>
<td>Second</td>
<td>10</td>
<td>0.1</td>
<td>Under the same conditions</td>
</tr>
<tr>
<td>Rate of error</td>
<td>%</td>
<td>1</td>
<td>0.1</td>
<td>Under the same conditions</td>
</tr>
<tr>
<td>Number of operators</td>
<td>Number</td>
<td>15</td>
<td>5</td>
<td>Under the same conditions</td>
</tr>
</tbody>
</table>
It can be seen that through the integration and docking of ERP and WMS, the industrial effects on storage capacity, handling capacity, response rate, rate of error, and number of operators for enterprises are very significant.

7. Conclusions

In this paper, an overall architecture of a sustainable digital factory is proposed, and the integration of ERP and WMS for an automated warehouse is studied. Then, an industrial realization and an implementation effect are studied. At last, a case study is given.

The research on the construction of a sustainable digital factory is focused on the concept and value of a sustainable digital factory, as well as the main contents and precautions of sustainable digital factory construction. However, there is still a lack of research on how to build a sustainable digital factory based on MES, especially from the aspects of framework construction, implementation path, index evaluation, etc.

This paper combines the method and technology of the middle table, and the realization of an automated warehouse based on the integration of ERP and WMS is studied to solve these above problems. A sustainable digital factory is the main way to realize intelligent manufacturing. MES is the brain and the core part of a sustainable digital factory. The enterprise adopts advanced intelligent and information technology to build and deploy the MES system platform, realize fine management and agile production, and meet the personalized needs of the market.

The main contributions of this study are as follows: (1) an overall architecture of a sustainable digital factory is constructed from the perspective of top-level design. (2) The method and technology of middle table is pro-posed for the integration of ERP and WMS for automated warehouse. (3) The industrial realization, implementation effect, and application cases of a sustainable digital factory based on MES are studied and given to solve these above problems. A sustainable digital factory is the main way to realize intelligent manufacturing. MES is the brain and the core part of a sustainable digital factory. The enterprise adopts advanced intelligent and information technology to build and deploy the MES system platform, realize fine management and agile production, and meet the personalized needs of the market.

As this paper mainly studies the top-level design, overall framework, system model, and other aspects of system engineering, it mainly uses qualitative analysis methods. Therefore, the main advantage of this paper is that it can guide enterprises to build a sustainable digital factory from a top-level and systematic perspective, and can reflect the systematic, comprehensive, hierarchical, step-by-step, and structural nature of the research. At the same time, the limitation of this paper is the lack of quantitative analysis methods such as configuration, optimization, and evaluation of the elements of the sustainable digital factory system. Therefore, in future work, qualitative and quantitative analysis
methods will be adopted to further study the construction of a sustainable digital factory, such as the configuration, scheduling, optimization, and evaluation of resources, manpower, equipment, systems, etc., in the automated warehouse.

**Author Contributions:** Conceptualization, Q.T. and X.Z.; methodology, Q.T.; software, Q.T. and X.M.; validation, Q.T.; formal analysis, Q.T. and X.Z.; investigation, Q.T. and X.M.; resources, X.M.; data curation, Q.T.; writing—original draft preparation, Q.T. and X.Z.; writing—review and editing, Q.T. and X.Z. All authors have read and agreed to the published version of the manuscript.

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