# Mixed reality-based digital twin implementation approach for flexible manufacturing system design

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# Abstract

Digital twin (DT) technology is essentially the equivalent mapping of the physical world in the digital space, and is therefore also considered to be a central technology to realize cyber-physical systems (CPS). Traditional DT implementations suffer from data diversity and lack of efficient visual human-machine interface while mixed reality (MR) technology provides a new possibility due to its powerful immersion and interactivity. In this paper, we propose an MR-based DT implementation approach for the flexible manufacturing system (FMS) design. Discrete event simulation model and mixed reality scene are applied to enable multiple users to collaboratively evaluate and optimize design schemes in a dynamic simulation way and an immersive and interactive environment respectively. In this approach, an improved particle swarm optimization algorithm is used to solve the facility layout problem which is one of the core problems of FMS design. Furthermore, the DT created in the design stage, which is a virtual representation of the physical FMS, can be extended to the whole FMS lifecycle, including the manufacturing and service stages. A case study of application on a real FMS is presented to illustrate the advantage of this approach.


# 1. Introduction

With the rapid requirement of mass customization manufacturing, traditional mass production is transforming to mass customization. FMS replaces the traditional single machine production mode, which adapts to the transformation from large quantities or flow production to multi-variety and variable batch production, and deals with large varieties with small quantities, few varieties with large quantities, mixed flow processing or urgent production. Under the background of Industry 4.0 & Intelligence Manufacturing, construction requirements of FMS or flexible and intellectualized reconstruction of production lines are increasing. In addition, when the product iteration leads to the change of process, the change of production batch, or the update of some old equipment in the FMS, the existing FMS needs to be reconstructed to meet the current production requirements. Therefore, it is necessary to put forward an efficient FMS design method that adapts to Industry 4.0.

The FMS design mainly focuses on performance indicators, linear type, auxiliary devices configuration (such as controller, cleaning machine, loader/unloader, etc.), machine tool configuration, layout, Material Handling System (MHS) design and control sub-system design. A proper design of FMS can minimize makespan, mean work in progress (WIP), and the number of machines, and maximize the production efficiency. Many scholars have done a lot of research on the methods of FMS design which mainly include mathematical and simulation-based methods. As for mathematical methods, M.E. Erdin et al. [1] calculated the number, utilization and sequence of workstations and plant layout using the bottleneck model and rank order clustering. M. Soolaki et al. [2] presented a 0-1 integer linear programming model for the multi-objective machine tool selection and operation allocation problem in FMS. J.A. Qudeiri et al. [3] used the genetic algorithm and artificial neural network to optimize the layout design of FMS. Because the mathematical method ignores the dynamic design factors, the simulation-based methods is proposed which are usually used with mathematical methods as a complementary tool to analyze dynamic behaviors. I. Um et al. [4] used systematic analysis methods combining a simulation-based analytic and optimization technique that is Multi-Objective Non-Linear Programming and Evolution Strategy. Current design methods are limited to mathematical and simulation-based methods, and more intelligent design methods adapting to Industry 4.0 need to be proposed.

A new possibility for design is provided by Extended Reality (XR) technology which includes Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). XR is characterized by interactivity and immersion, which transforms the design pattern to three-dimensional immersive and interactive environments and displays the design details more intuitively comparing with two-dimensional drawings and three-dimensional models. XR has been used in various design and manufacturing activities which include XR collaborative design [5], robot path planning [6], plant layout [7], maintenance [8] and virtual assembly [9]. The immersive and interactive environment based on XR can simulate the manufacturing process of an FMS being designed to evaluate the design, which can be regarded as a supplement of mathematical and simulation-based hybrid methods. As for the related application attempts including the design of manufacturing systems and production lines, Malik et al. [10] used VR for the design of human-centered production systems and developed a unified framework to integrate human-robot simulation with VR. Peruzzini et al. [11] researched the application of VR to create virtual manufacturing simulations of assembly tasks to design assembly lines. Jiang et al [7]. used AR to provide visualization of the layout process. Discrete event simulation (DES) and XR in combination provide new opportunities and future trends for factory design and layout, product and service development, and industrial plant decision-making and control [12]. Karlsson [13] used simulation and MR to show a simulation model in 3D with Microsoft HoloLens and a bottleneck detection method has been applied. In the design process of a manufacturing system, XR can be used to simulate the operation of the system to improve the immersion and interactivity of the simulation compared to traditional simulation software (such as *Siemens Plant Simulation*).

In addition to serving as a human-machine interface during the period of the design, XR can also be used to build a virtual representation of physical entities named digital twin (DT) to mirror the status of entities using simulation models and intelligent sensing methods. Under the implementation of Industry 4.0 and Intelligent Manufacturing strategies and technical support of Internet of Things (IoT), Industrial Internet, Big Data Analysis and XR, DT has become a popular research topic and the theoretical framework has been continuously improved. DT has been adopted in various areas of the manufacturing industry including product design and manufacturing [14, 15], smart factory implementation [16–19], manufacturing system or production line design [20–23], job-shop scheduling [24, 25], and prognosis and health management [26]. However, applying DT to the design of manufacturing systems or production lines is in the preliminary attempt stage and related researches are incomplete. Leng et al. [20] proposed a novel digital twin-driven approach for rapid reconfiguration of automated manufacturing systems and put forward a two-part DT which comprises the semi-physical simulation and optimization. Zhang et al. [21] proposed a digital twin-based approach for rapid individualized designing of the hollow glass production line and the digital twin merges physics-based system modeling and distributed real-time process data to generate an authoritative digital design of the system at the pre-production phase. Guo et al. [22] proposed a modular approach to build DT which can help designers evaluate different designs and find design flaws. Jiang et al. [23] discussed how to effectively create a DT model during the design stage of a complex manufacturing system and to make it usable throughout the system's lifecycle. To be specific, they adopted a three-dimension DT model including logical, geometric and data models, and proposed a new interconnection and data interaction mechanism between the physical system and its virtual model. Other studies focus on the use of XR as the human-machine interaction interface in DT. Ke et al. [27] designed an enhanced interaction framework based on VR/AR/MR in digital twin. Luis et al. [28] presented a methodology for creating a digital twin of the manufacturing process with an immersive VR interface to be used as a virtual testbed before the physical implementation. Zhu et al. [29] use Microsoft HoloLens to visualize the DT data of a CNC milling machine in a real manufacturing environment and provide an intuitive and consistent human-machine interface. These studies are not related to the design phase, and the applications are limited to the process of manufacturing. Accordingly, in inspiration of the above researches, it is worthwhile to explore the application of a combination of XR technology and DT for FMS design, or even for the FMS lifecycle. And in the design stage, how to build the DT which can be extended to be usable throughout the FMS lifecycle including the manufacturing and service stage remains a problem.

MR is developed by VR and AR and has the advantages of both, and can overlay the virtual models to the real world, which might be more suitable for the application of the industrial field. Since there are still few industrial applications of MR that can improve the immersion and interactivity of the simulation in the design stage and provide a friendly immersive visual human-machine interface of DT, an MR-based approach for FMS design and digital twin implementation is proposed. The approach is designed to efficiently evaluate the dynamic characteristics of the designed system and to create an immersive environment. Based on intelligent algorithms, simulation and MR technology, the design, simulation, visualization and optimization of FMS can be integrated. Building FMS virtual scenes and simulation models has the following two clear advantages: one is the contribution to exploring the FMS' dynamic characteristics of the complex multi-factor interaction and analyzing the bottlenecks of the system to improve the design reliability and validity; the other is that in an immersive environment, it can mirror the real-time running state and multi-user interaction state of the simulation model or real FMS to build DT and achieve Cyber-Physical fusion.

The rest of the article is organized as follows. A framework of the MR-based approach for designing FMS and DT implementation is proposed in Sect. 2, and the key supporting technologies are introduced. Sect. 3 validates and demonstrates the proposed method with an application case. In Sect. 4, the results are discussed and the conclusions are presented.

## 2. Framework And Key Techniques

# 2.1. A framework of MR-based approach for FMS designing and DT implementation

As shown in Fig. 1, in order to realize the digitization, intellectualization and visualization of FMS design, a DT implementation approach for the FMS design based on MR is proposed, which adopts improved mathematical and simulation-based hybrid methods with an MR-based immersive interactive human-machine interface to rapidly construct the DT of the whole lifecycle from design, manufacturing to service. In the FMS design, in contrast to traditional mathematical and simulation-based methods, XR technology is introduced to enhance the immersion and interactivity of the simulation. DT is built in the design stage and it can be extended to be usable throughout the FMS lifecycle including the manufacturing and service stage. The design of FMS is divided into six stages: conceptual design, detailed design, creating a prototyping of DT stage, final design stage, and extension of DT stage. The optimization algorithm, one of the mathematical methods to solve the core design decision problems, is used in the detailed design phase, and the simulation-based method is used in the final design phase. The main improvement of this method is to introduce DT construction into the design process, and use MR technology in creating a prototyping of DT and final design stage.

*Conceptual design stage:* the FMS's performance indicators are determined preliminarily according to the design requirements document, the linear type (straight single line, straight multiple lines, ring, etc.) is selected, and auxiliary devices are configured.

*Detailed design stage:* With the assistance of CAD and CAM, the processes of the parts to be manufactured in the FMS are optimized. According to the processes, the machine tools are configured, and the facility layout is designed by the intelligent algorithm which will be described in Sect. 2.2. In addition, MHS design, control strategy design, software design are also carried out in this stage.

*Creating a prototype of DT stage:* MR technology is applied to build a virtual immersive scene, and the DT in the design stage of FMS is constructed to realize the virtual-real fusion. The construction of DT is typically based on physical machines or workshops. The details are described in Sect. 2.3.

*Final design stage:* After the discrete simulation model is built, the design scheme is simulated in simulation software *Plant Simulation* with expected production plans and simulated in the DT created in the former stage. According to the simulation results, the mapping of DT and the judgment of the clients, the design scheme may be adjusted, including changing the machine tool configuration and layout, MHS and processing control strategy. The details are described in Sect. 2.4.

*Extension of DT stage*: The DT created in the former stage can be extended to the actual manufacturing process application. The processing data and material transport data of the FMS site are visualized in real-time in the DT. DT oriented to the whole life cycle of the FMS is built to realize the cyber-physical fusion between virtual scene and physical entity and build the cyber-physical flexible manufacturing system (CPFMS). The details are described in Sect. 2.5.

As for the conceptual design and detailed design stage, many scholars have carried out a lot of research work and obtained some relatively mature and reliable methods. This paper focuses on the rest design stages and the DT implementation of the whole life cycle based on MR.

## 2.2. Solving the FLP of FMS in the detailed design stage

In the detailed design stage, facility layout design is one of the core problems, which directly affected the utilization rate of the machine tools, the takt time, the logistics cost and the quantity of WIP. The facility layout optimization design problem aims to obtain the optimal resource allocation, material flow and logistics transportation scheme. FMS Facility Layout Problem (FLP) is a typical NP-hard Problem and is simplified according to characteristics of FMS including replacing irregular machine tools with regular rectangles, setting the minimum distance between machine and site edge and the minimum distance between machines in two directions as fixed values, the center point of machines in the same row is on the same line, and the material exchange takes place on the center point.

The closeness between adjacent machines is defined by dividing the logistics volume between them by the total logistics volume. The minimum total logistics volume of system $C_1$ can be calculated using equation (1) and the maximum sum of closeness $C_2$ can be calculated using equation (2). $C_1$ and $C_2$ are taken as the optimization objective, and the optimization objectives will be transformed into a single objective $C$ which can be calculated using equation (3)

$$C_1 = \min \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij} d_{ij}$$

1

$$C_2 = \max \frac{\sum f_{\mathrm{adj}}}{\sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}}$$

2

$$C = aC_1 + b\frac{1}{C_2}$$

3

The boundary conditions are: 1) the machine boundary does not exceed the specified region; 2) machines in the same row do not overlap with each other.

The particle swarm optimization (PSO) algorithm is chosen to solve the FLP of FMS, in view of it has a faster search speed and better global search capability. Aiming at the solution of FLP of FMS, tabu search algorithm and adaptive mutation are introduced to improve the traditional PSO algorithm to prevent it from falling into a local optimal.

The fitness function is shown in Equation (4)

$$F = aC_1 + b\frac{1}{C_2} + k_P P$$

4

## 2.3. Creation of virtual scene of FMS

Upon accomplishing the conceptual design and detailed design, the preliminary FMS design scheme is obtained and the DT is about to be born in the design stage. Constructing DT from the design stage and applying DT to actual manufacturing process is conducive to expanding the application of DT and realizing the full lifecycle application. Given the problems of poor interactivity and lack of immersion in digital models, it is reasonable to develop FMS virtual scene with high visualization, strong human-machine interaction and deep immersion based on 3D models to verify the design scheme through virtual simulation.

In this paper, we employ MR to establish immersive and interactive virtual scene, which can provide human-machine interface for DT. Compared with MR, VR offers virtual scenes where users cannot observe the real world, while AR integrates the real environment with digital objects. In AR scenes, virtual objects are geometrically matched with real objects in the real environment and superimposed scenes are generated through human-machine interaction. However, AR does not have the ability of environment perception, e.g., it cannot generate inter-occlusion with the real environment. MR is developed from AR and VR, and is a state in between. MR supports real-time interaction between users and virtual models, users and physical objects, and physical objects and virtual models, and adds the function of spatial awareness.

The head-mounted display (HMD) is the main device of the XR, enabling enhanced display. HoloLens is a holograph-supported typical MR HMD device developed by Microsoft. It has interaction modes such as Gaze, Voice Command and Gesture, and supports UWP applications. Users wearing an HMD are placed in an immersive scene to improve the immersion and interactivity of virtual-real mapping visualization. People can also be integrated into the cyber-physical system to construct the human-cyber-physical system (HCPS) [30]. As a ubiquitous interface, MR enhances the interaction between human operators and the manufacturing environment and can respond to the manufacturing environment on time [31].

Hence, the development process of the MR scene is shown in Fig. 2. First of all, according to the facility layout, MHS and auxiliary devices designed in the conceptual design and detailed design stage, the 3-dimensional model of FMS is built in 3-dimensional CAD/CAM software (such as *Solid Edge*), and the STP format file is exported. Then, open the STP file in 3ds Max software, render the model with mapping and material setting, and export the FBX file which contains the model, material, camera and other information. Next, import the FBX file into VR engine software named Unity 3d, build the virtual FMS scene. Finally, apply Microsoft MRTK (Mix Reality Toolkits) open-source toolkit, and write scripts with C# language to develop the corresponding functions of the virtual scene and network communication module to complete the development of HoloLens client UWP software.

The communication network is set up to enable the MR scene based on HoloLens to support the collaborative work of multiple users, so that they can share the same virtual scene in the same place or different places. In this way, the same model can be viewed, interactive or analyzed, and the simulation or real running state of the FMS and the interaction state of multiple users can be displayed in a distributed way. The multi-device communication framework is shown in Fig. 3.

There are several modes in virtual scenes available for users to choose from, including Roaming mode, Overview mode, and Dynamic Interaction mode. In the Roaming mode, people can wander in the scene, observe the details of the designed scheme, and simulate the feeling of walking in the real FMS. In the Overview mode, the entire FMS model is scaled and fixed on the table to show the whole system in the form of a virtual sand table. In the Dynamic Interaction mode, the machines can be moved, rotated and scaled through gesture interaction, gaze interaction and voice interaction. Besides, the key information of the machine can be displayed by touching interaction, the machine running process can be simulated and the scene can be shared by multiple HoloLens's users.

## 2.4. Simulation analysis and design modification in the final design stage

In the final design stage, simulation verification and virtual presentation of the design scheme as well as the final adjustment design are carried out. The virtual simulation process in the final design stage is shown in Fig. 4.

On the one hand, according to the design scheme obtained in the detailed design stage, adding with the expected production plan, the process characteristics of the parts to be processed and the parameters of the processing machines, discrete event simulation software (such as Witness, Flexsim, Siemens Plant Simulation, etc.) is used to simulate the FMS production activity. In this way, the performance evaluation index of FMS is analyzed, such as machine utilization rate and bottleneck. By analyzing the simulation results, the reliability and rationality of the above machine configuration, layout design and MHS design are verified. When a certain machine utilization rate in the FMS is too low or the variance of the utilization rate of each machine is too large, the design scheme should be modified and adjusted, including the adjustment of machine configuration and layout, logistics scheme, etc.

On the other hand, stakeholder customers can share and interact with distributed virtual scene based on MR developed above to view and analyze the design scheme, and then put forward suggestions for modification if the design is not satisfactory.

## 2.5. Implementation of the digital twin of FMS

DT can be applied in different stages from FMS planning and design, actual production to service, and plays a role in the whole FMS life cycle. DT is not only a virtual immersive display in the design stage, but also a real-time dynamic synchronization of FMS. The DT is built from the design stage and then extend it to full life cycle applications. A five-dimension model for the DT as shown in Fig. 5 is adopted, which includes physical FMS (PFMS), virtual FMS (VFMS), FMS service system (SS), DT data (DTD) and the connection between each part [32]. PFMS is the objective existing entity, and VFMS is the virtual scene deployed in the MR device mentioned above with specific functions of visualization, interaction and data transmission. SS is an integrated service platform, creating interfaces with MES, ERP and other information management systems, and provide service modules based on algorithms or computer-aided tools for the needs of VFMS and PFMS. DTD is the medium of data exchange and data storage among the above three. The mapping relations among PFMS, VFMS, SS and DTD are as follows: the actual state of PFMS drives the synchronization of VFMS, and the instructions of VFMS can be fed back to PFMS to make corresponding adjustments; SS provides the management of production to ensure the normal operation of the PFMS. SS manages and analyzes the data of the PFMS, optimizes the production mode, and sends the control instructions to PFMS which are verified in VFMS in advance.

Table 1
The characteristics of DTs applied in different lifecycle phases.

| **Phase** | **Design**<br><br>**(before production)** | **Manufacturing**<br><br>**(during production)** | **Service**<br><br>**(after production)** |
|---|---|---|---|
| **Function** | Virtual visualization scene;<br><br>Immersive and interactive scene;<br><br>A static perspective | IntelliSense;<br><br>Virtual-real mapping;<br><br>A real-time synchronization | Data management and analysis; manufacturing optimization; breakdown prediction and maintenance;<br><br>an optimization and prediction service |
| **Simulation mode** | Off-line simulation | On-line simulation | Predictive simulation |
| **Objective** | Immersive visualization of the design | Intelligent production management | Intelligent production service |
| **Creating process** | Preliminary DT:<br><br>interactive mode and collaboration communication framework are designed. | Based on Preliminary DT, the connection between the physical machines and the virtual scene, between the virtual scene and the service system is built, and the data storage and transmission architecture are designed. | The data analysis model is designed to optimize and predict the manufacturing process. |
| **Main DTD** | Design data and simulation data | Processing data of each machine, sensor data, material handling data, control data, service system data | Calculation results data of the optimization or prediction model |

The characteristics of DTs applied in the design, manufacturing and service phases are shown in Table 1.

In the design phase, DT is a static perspective combing with an off-line simulation model, which is used to visualize the design scheme after the conceptual design and detailed design showing it to the design and development personnel, the customer, and simulate the production plan for verification in an immersive and interactive scene. The static perspective consists of the various modes of the virtual MR scene described in Section 2.3. The off-line simulation model is established in the simulation software, and the production capacity of the design scheme is simulated and verified according to the expected production plan of FMS. In this stage, the data stored in DTD mainly includes design data and simulation data. DT in this stage mainly constructs the virtual model and the bidirectional connection between the virtual model and DTD.

Based on the DT constructed in the design phase, the connection between the PFMS and DTD, as well as the connection between the SS and DTD, can be constructed, which is suitable for the actual manufacturing process of FMS. The real-time data sensing function of PFMS is a necessary condition for extending DT, which can be realized through sensors, radio frequency identification (RFID) and other major data sensing components. The data exchange model between PFMS and DTD is established based on real-time data sensing collection function, data transmission model, QR code recognition and data sharing of CNC system. Since there are many kinds of devices and many transmission interfaces and transmission protocols between them in FMS, it is necessary to use a common communication protocol to eliminate barriers to data transmission between devices. OPC UA is a standard communication protocol that can be used for data interaction and real-time data acquisition between different devices in FMS. OPC UA is used to model the information of all the devices in the PFMS, and all the information is described based on a unified standard protocol, format and language to facilitate the flow of information.

DT applied in the FMS manufacturing phase realizes Cyber-Physical fusion, virtual and real mapping. The order data, processing process data, material handling data, data in ERP/MES system, sensor data and data in NC system in the PFMS are stored into DTD in real-time. The virtual model obtains the data in DTD, which can drive the virtual model to realize the visualization of the processing state synchronously. The SS established the data communication channel between ERP, MES, CNC system, to realize the bi-directional data exchange and function integration. Bus technology is used to realize FMS information control, including automatic delivery of production plan, automatic transmission of NC codes, machine operation monitoring. Equipped with equipment monitoring and planning management functions, it can improve the digital management level of the parts process chain, further improve the processing efficiency and reduce costs.

DT applied in the FMS service phase, integrates the function of data management and analysis, manufacturing process optimization and prediction. An Optimization and Prediction Service Module is added based on DT applied in the manufacturing process. The data analysis model is designed by using the processing data, and the data of the optimization or prediction calculation results are fed back into DTD. The collected real data of the production process are classified and managed. The data analysis model is used to analyze the utilization rate of FMS CNC machine tools, production bottlenecks to evaluate the rationality of the processing schedule, predict the production capacity of FMS under different order plans, and judge the abnormal processing state. DT applied in the FMS service process realizes intelligent production service, which adjusts the production plan, optimizes the production schedule and predicts the failure and processing capacity based on the analysis of the field processing data.

## 3. Case Study

Aiming at the processing of gearbox shell parts, an automobile manufacturing company plans to build an FMS to realize flexible and efficient production with multiple varieties and small batches.

The main parts to be processed in this FMS are aluminum alloy adapter plate part A, box cover part B, box body part C, the processing routes are shown in Table 2. Through the analysis and optimization of the parts process, the horizontal machining center and vertical machining center are used for processing.

Table 2
The processing routes of parts A, B and C.

| Parts | Processes |
|---|---|
| A | M4→M1→M2→M3 |
| B | M2→M3 |
| C | M2→M3→M5→M6 |

As shown in Fig. 6, the FMS digital design and virtual simulation system developed by us is used to complete the conceptual design and detailed design, which integrated parts/ equipment/ process management, layout design optimization algorithm and DES software interface.

In the design platform, according to the process of parts A, B and C, 9 machines of 6 types named M1-M6 are selected, of which M2, M3 and M4 are equipped with two and the others are equipped with one. Then, MHS is designed and auxiliary devices are configured. After setting the layout parameters, the improved particle swarm optimization algorithm (AMPSO) built into the system is used to solve the facility layout problem. Next, the simulation software *Plant Simulation* is called, and the design data is passed into the simulation software through the developed interface to complete the automatic modeling, which is realized by modifying the pre-established basic general model, as shown in Fig. 7. The simulation software verifies the validity of the design scheme, simulates the actual manufacturing process, and analyzes the utilization rate of each machine. If obvious design defects are found in the design scheme through simulation, such as too large variance of utilization rate or too low utilization rate of certain equipment, it is necessary to go back to modify the design scheme and repeat the above process.

Based on the above design scheme, the virtual scene of FMS is constructed, and the DT of FMS design stage is constructed. According to the design scheme, the corresponding machine models in the 3D model library are selected to construct the overall 3D digital model of FMS. The virtual scene is built on the basis of 3D digital model, and the roaming, interaction and other functions of the virtual scene are developed with the Unity 3d engine, and the UWP App is generated and deployed in the MR device HoloLens. Users wear HoloLens (as shown in Fig. 8 (a)), open the main menu and touch the icon of the deployed App (as shown in Fig. 8 (b)), and enter the application. Various functions of the immersive and interactive scene can be used to check every detail of the design scheme, evaluate the design scheme, and put forward corresponding opinions. As shown in Fig. 8 (c), after entering the App, four modes of Roaming, Interaction, Overview and Multi-device connection are selected through the user interface. These four modes have significantly different characteristics and functions.

In the Roaming mode, the size of all virtual models is exactly the same as the real size of the machines, and the size and position of the virtual model are fixed. Users can roam in the virtual scene, check the details of the device and immerse themselves in the FMS design scheme. **Figure.8** (d) is the effect of simulating the roaming scene in Unity, and Figs. 8 (e)-(f) is the real effect in HoloLens.

In the Interactive mode, models in the scene can be adjusted in orientation or size, and users can interact with virtual models in the scene. Interaction includes gesture interaction, gaze interaction and voice interaction. Gesture interaction means that when the user's hand is close to the corresponding model, the *Bounding Box* of the corresponding model will be triggered. The user can scale and rotate the model by stretching the vertices and side control points of the bounding box, as shown in Fig. 8 (g). Besides, users can also grasp the corresponding device by hand and move to the target position to complete the movement of the virtual model. Gaze interaction means that when the user gazes at a model, the *Tool Tip* is triggered, which will display the main information of the model and hide when the user's eyes are away from the model. Voice interaction is embodied in gesture interaction and hand gestures can be completed by preset voice keywords. For example, after triggering the *Bounding Box*, the model can be rotated to the preset specified angle through the voice "rotate". With gaze interaction, gaze at a model and move the model to the nearest location through the voice "come".

In the Overview mode, the virtual FMS is scaled, and the size and position of the whole scene are fixed. Users can observe the whole design scheme of the FMS from any position around the virtual FMS to achieve the effect similar to the electronic sand table, which is also called "God's perspective". The real effect of HoloLens is shown in Fig. 8 (h).

In Multi-device connection mode, multiple devices can realize distributed interaction at the same location or different locations. Multiple devices communicate asynchronously through Socket to realize the synchronization of anchor points and interactive information in 3D model space.

After the final FMS design scheme is applied in construction, DT in the design stage is extended to manufacturing and service - full life cycle application. The mapping between virtual models and physical entities is established, the connections among the service system, virtual models and physical entities are improved, and the data exchange channels among physical entities, service system and DT Data are established. Firstly, a sensor-based data perception and transmission subsystem of the object entity is established to realize the bi-directional transmission between the machine tool data and DT data.

Secondly, the processing process data of machines is transmitted to the virtual model in real-time through DT data, so as to realize the synchronous visualization of the processing process. Lastly, the service system establishes a data interface with CNC system, ERP system and MES system to realize data exchange and function integration.

# 4. Conclusion

Based on mixed-reality technology and mathematical and simulation based methods, this paper focuses on the design method of FMS and the construction of DT of FMS lifecycle. In the detailed design stage, the AMPSO-TS algorithm provides an optimal scheme for facility layout. Using the model in the design library, the design scheme is transformed into a 3D model, and then the MR scene is built, and the DT of the FMS design stage is constructed, which provides an immersive and interactive environment for visualization, interaction and simulation of the design scheme. Using MR virtual scene and DES model simulates and evaluates the design scheme to put forward modification suggestions. When the design of the FMS is completed, OPC UA protocol is used to establish the connection between the actual FMS and the virtual scene. Meanwhile, the service system is improved, so that the application of DT can be extended to the manufacturing and service stages to realize the full life cycle application of FMS.

The main contributions of this paper are as follows: 1) The design process of FMS based on MR is standardized and integrated with DT construction. The DT created during the design stage remains available throughout the FMS lifecycle, including the manufacturing and service stages. 2) MR is introduced into the design of FMS for the DT implement to provide an immersive and interactive environment and improve the visualization of the design process. 3) The layout optimization algorithm in the design stage is modified to improve the performance of the traditional PSO algorithm and the rationality of layout optimization.

# Abbreviations

| $n$ | **Total number of machines** |
|---|---|
| $d_{ij}$ | Distance from machine *i* to machine *j*: the absolute value of the difference between the coordinates of machine *i* and the coordinates of machine *j* |
| $f_{ij}$ | Logistics coefficient per unit distance between machine *i* and *j*: the value of the flow rate times logistics cost coefficient between machine *i* and *j* |
| $f_{\text{adj}}$ | Logistics coefficient between adjacent machines which are in the same row or adjacent rows |
| $a$ | Weight coefficient of the objective function 1 |
| $b$ | Weight coefficient of the objective function 2 |
| $k_P P$ | Penalty function |

# Declarations

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# Figures

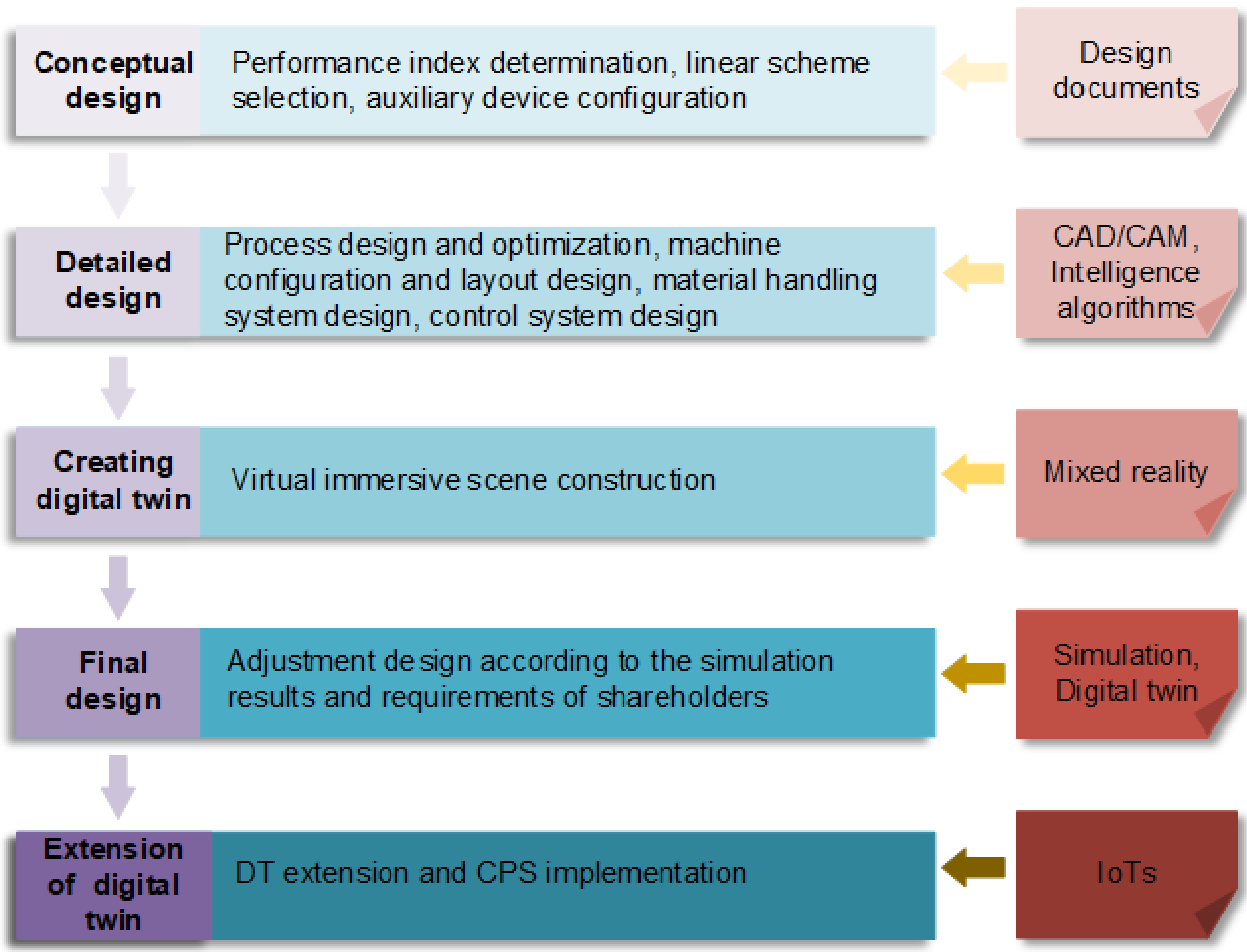



Figure 1

The flow chat of FMS design and DT implementation approach based on MR

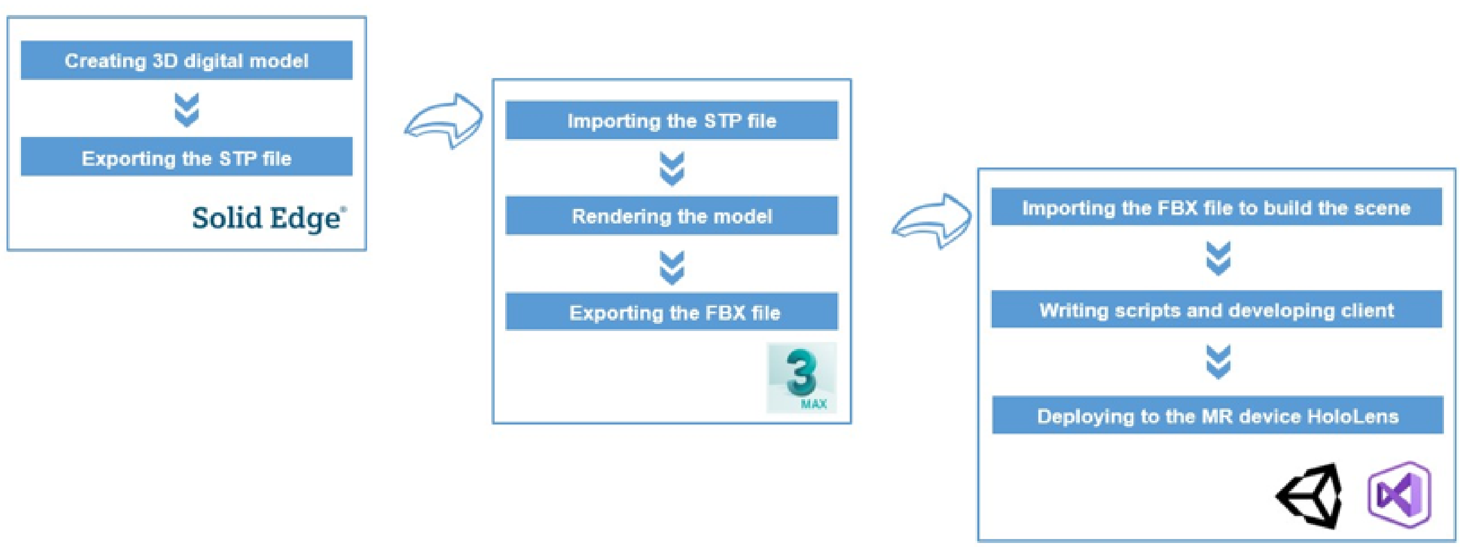



Figure 2

The development process of the MR scene

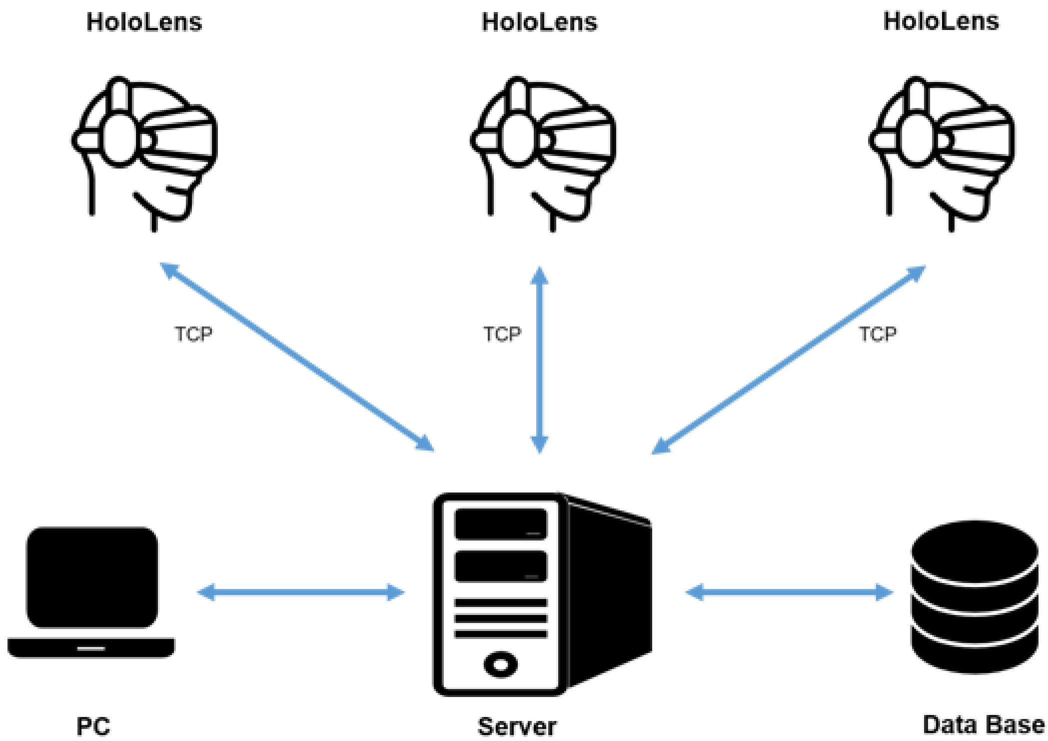
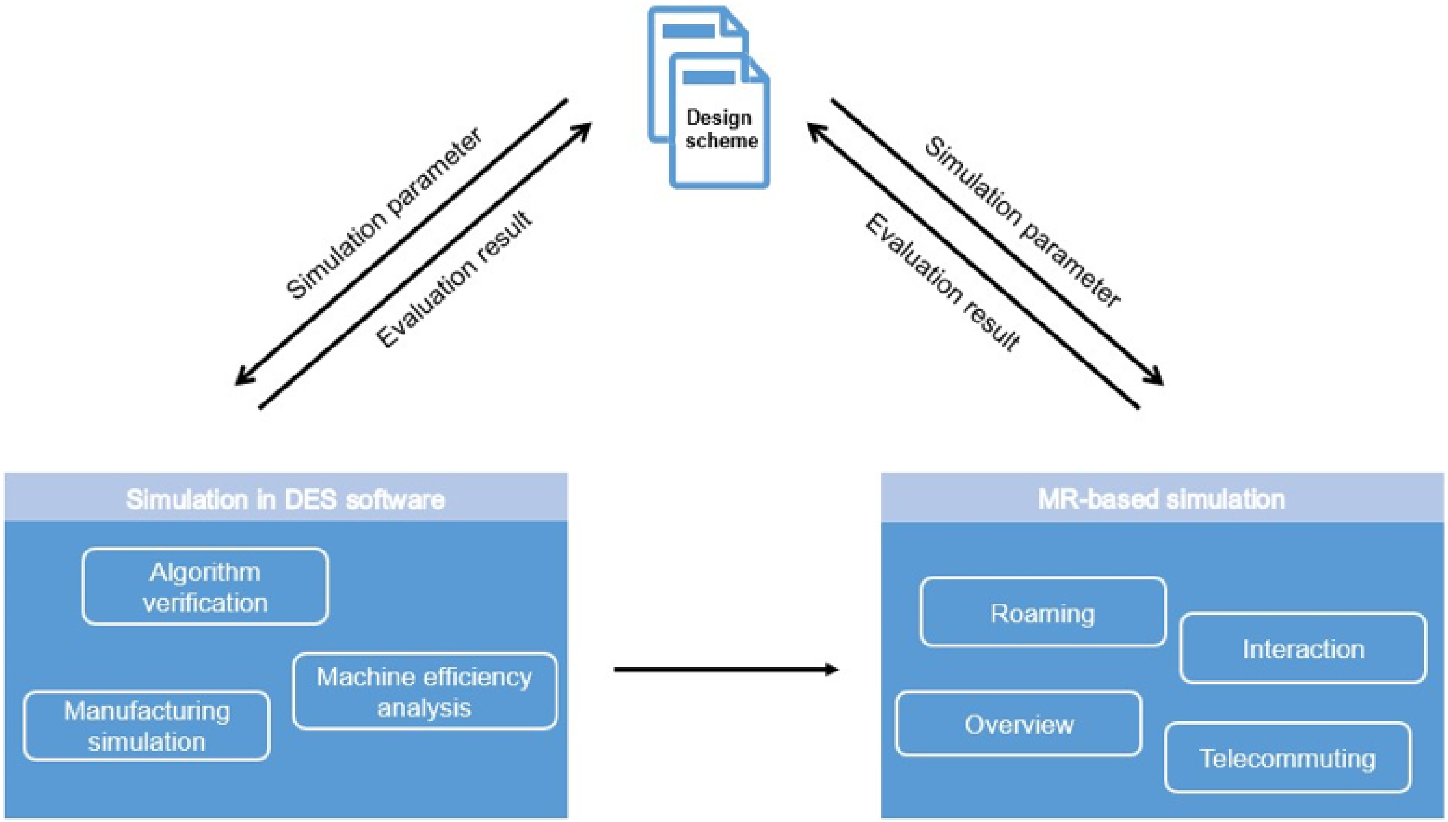


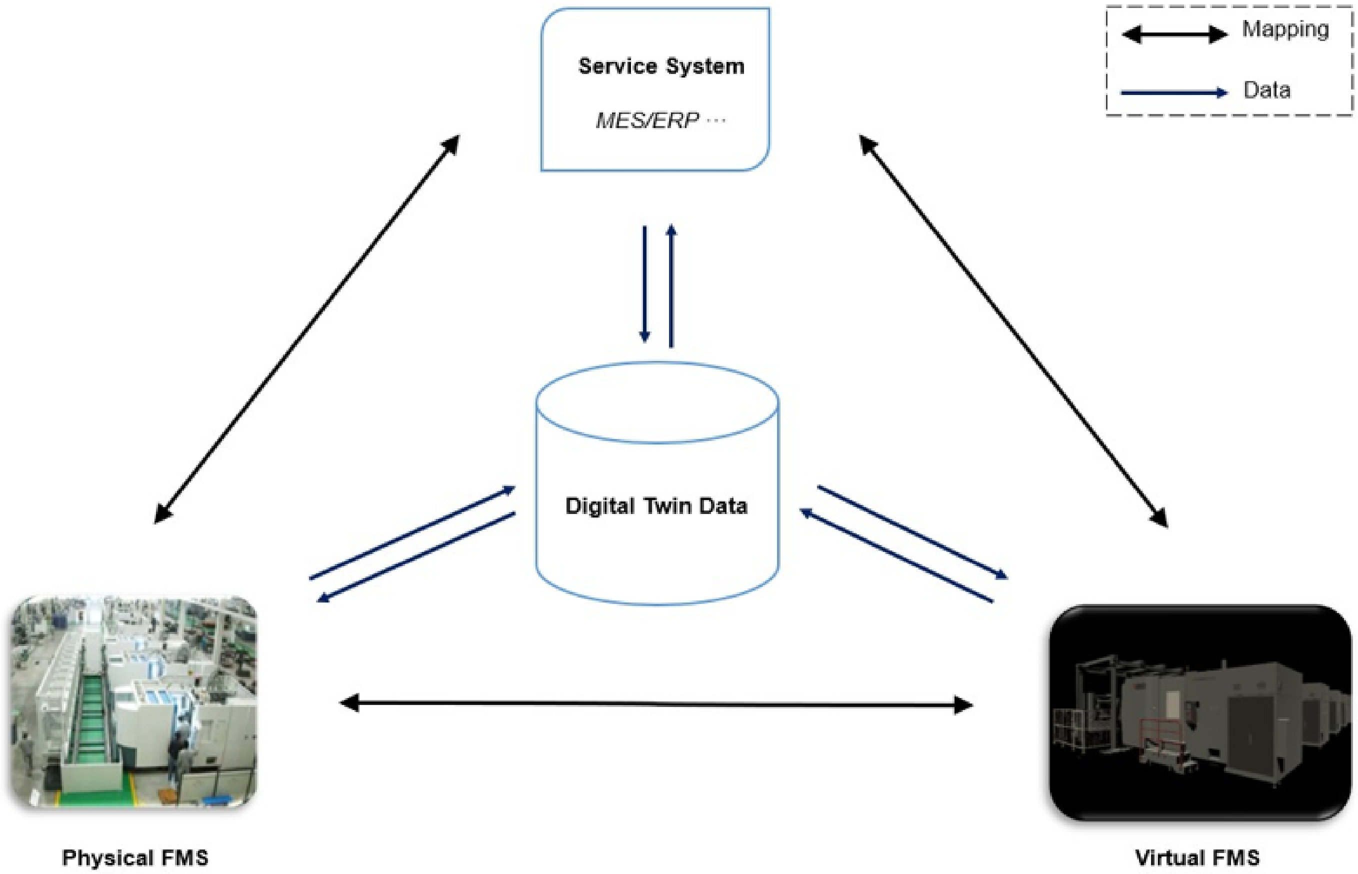

**Figure 3**

The multi-device communication framework of the MR scene



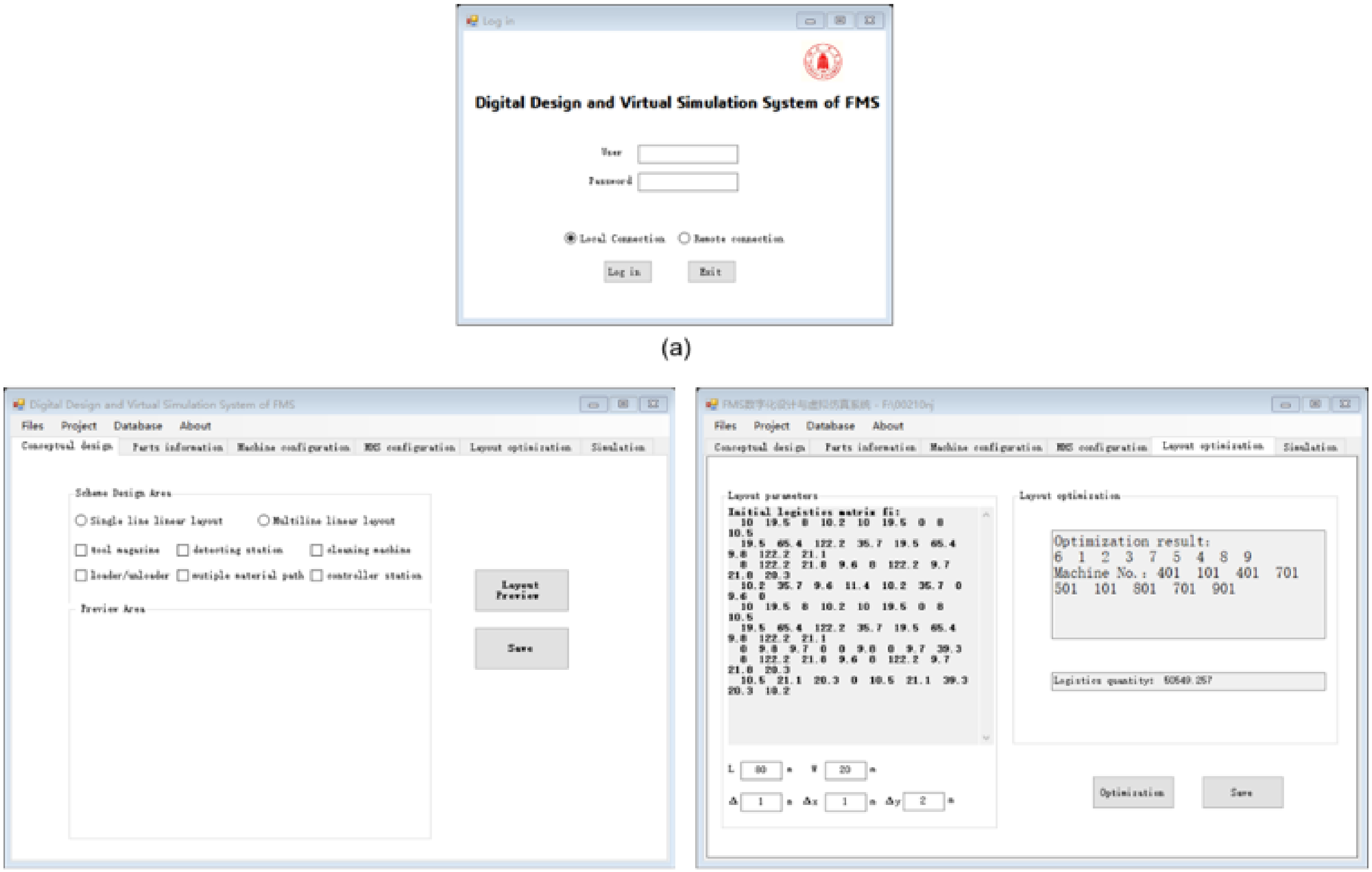

### Figure 4

The virtual simulation process in the final design stage




## Figure 5

Five-dimension model for the DT

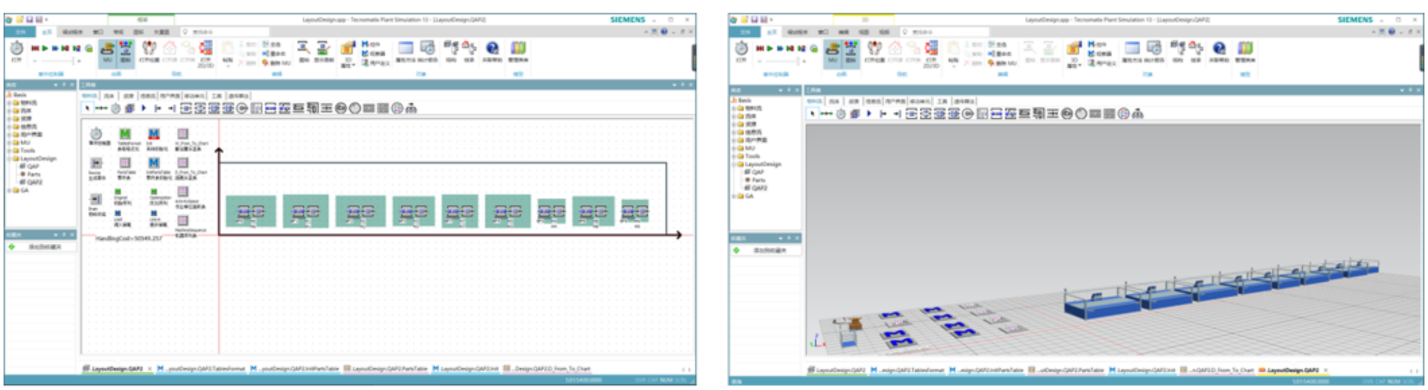



(a)

(b) (c)

## Figure 6

The interface of the FMS digital design and virtual simulation system: (a) login interface; (b) conceptual design interface; (c) layout optimization interface



(a) (b)

## Figure 7

The simulation in *Plant Simulation*: (a) 2D mode; (b) 3D mode

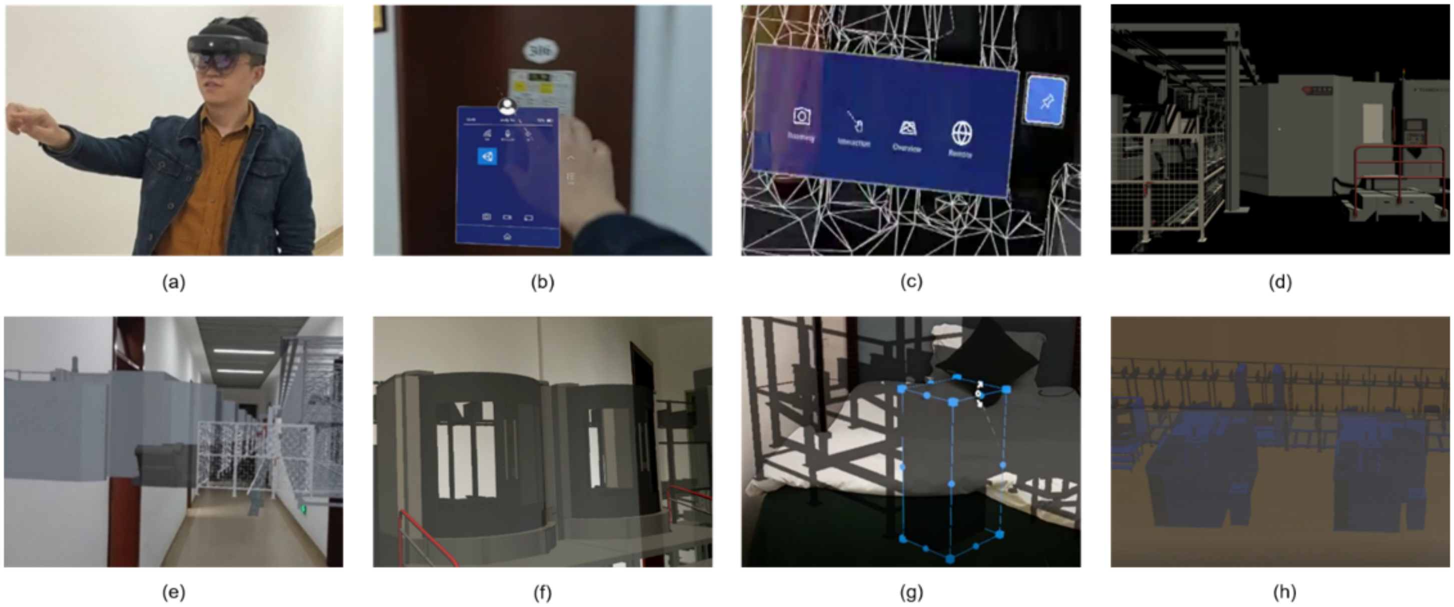


Figure 8

MR scene in HoloLens: (a) wearable method of HoloLens; (b) the App icon; (c) user interface of the App; (d) the roaming scene simulating in Unity; (e) the roaming scene in HoloLens; (f) a detail of roaming scene; (g) the Interactive mode; (h) the Overview mode