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ORIGINAL ARTICLE

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# Model construction of planning and scheduling system based on digital twin

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**Abstract**
The emergence of uncertainty factors will exert a strong influence on the accuracy of workshop scheduling. Digital twin' technology and planning and scheduling are integrated to form a planning and scheduling system based on digital twin, which can effectively use the concept of twin to carry out all-around management and control of the uncertain factors in production activities so that the planning and scheduling scheme in the production process can accurately guide the actual production. Firstly, the system establishes management and control mechanism of planning and scheduling system based on digital twin. Second, it establishes a digital twin model of the planning and scheduling system for the management and control mechanism. Finally, the key technology of the planning and scheduling system is expounded, which mainly includes the perception and collection of total production factor information and the planning and scheduling prediction. In order to verify the validity of the scheme, the planning and scheduling system suited for the enterprise is designed and developed in combination with the frame workshop.

**Keywords** Digital twin · Uncertainty · Planning and scheduling · Management and control mechanism

## 1 Instruction

Production planning mainly solves the problem of what and how much to produce in a workshop, which is mainly decided by upstream customers. Production scheduling is concerned about when and where production begins in a workshop, which is mainly determined by the workshop resources. According to the upstream customer's order requirements and actual situation of the workshop, the best scheduling scheme for completing the order can be determined, so that the final product can be accomplished with standard quality and quantity in the specified time that customer stipulated [1]. When planning and scheduling is used to guide the actual production, there will be external changes in customer orders and internal changes in personnel, equipment, materials, etc., such as material missing, personnel flow, equipment fault, product quality not up to standard, etc. These changes are collectively referred to as uncertainty factors.

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Due to the low transparency of the existing workshop information, when these uncertain factors appear in the production, it will seriously hinder the formulation and implementation of the scheduling plan in the time dimension. In this aspect, it is the breakthrough point that we can predict the uncertain factors that may appear in the production process through the transparent data of the workshop, and take relevant measures in advance, which can form a plan and scheduling scheme to guide the actual production accurately. Digital twin provides technical support for this breakthrough point.

The digital twin, firstly proposed in 2003 by Dr. Michael Grieves, a professor at the University of Michigan in the USA, is defined as making full use of the data such as physical model, sensor update, operation history etc. and integrating the simulation process with multi-disciplinary, multi-physical quantities, multi-scale, and multi-probability to realize the mapping that can be completed in virtual space, so as to use it to reflect the corresponding entity equipment life cycle process [2]. It is firstly applied to the health maintenance of aircraft, then experts and scholars analyze its characteristics and apply digital twin technology to different fields such as production workshop, equipment failure prediction, and health management [3]. At present, although the twin workshop can realize the transparency of the physical workshop [4], the literature on the planning and scheduling based on digital twins is rare.

At present, the research of uncertainty factors in dynamic scheduling mainly focuses on the following three points. First, historical data is often used to predict the occurrence probability and distribution characteristics of uncertainty factors in the modeling process. When there are uncertainty factors such as product demand change and working condition change, they can be introduced into the mathematical model and algorithm according to the real-time situation of uncertainty factors to reschedule the planning and scheduling scheme. Common methods include random planning, fuzzy planning, robust optimization, and so on. Lin et al. used the triangular fuzzy number to describe the fuzzy processing time to solve the problem of uncertainty processing time in the scheduling process [5]. An algorithm is proposed by Lei et al. and other methods to study the problem of flexible work scheduling with maximum fuzzy completion time to optimize the target [6]. In order to improve the stability and robustness of the scheduling of the processing workshop under the faulty environment of the machine, He et al. proposed a scheduling strategy based on the distribution of machine failure and the comprehensive application of idle time insertion method, right-shift rescheduling strategy, and path change rescheduling strategy [7]. Briskorn et al. proposed inserting machine failure and service time into idle time for robust scheduling and proposed three strategies for inserting idle time [8]. Lu et al. considered uncertain events into the scheduling model and used different methods to deal with it [9–11]. Second, production data-driven scheduling. Luo et al. used RFID technology to deploy advanced wireless devices to value-added points to create real-time workshop data collection and synchronization. And on this basis, a multi-stage hierarchical scheduling mechanism is proposed for real-time scheduling [12]. Qu et al. developed a data-driven distributed reinforcement learning method for learning and searching dynamic scheduling strategies in large-scale random processing networks [13]. Azadeh et al. trained the artificial neural network by using the partial scheduling sample dataset obtained from the job shop scheduling simulation, and then searched in the complete candidate scheduling rule set by using the trained artificial neural network model to find the scheduling rule combination of a job machine that can minimize the completion time of the current workshop production task [14]. Third, dynamic scheduling based on prediction. Kong et al. used a virtual data center to provide a fuzzy prediction method for uncertainty workloads and fuzzy availability of virtual nodes and proposed and evaluated an online dynamic task scheduling algorithm SALAF [15]. Ji et al. proposed a fault prediction method based on big data analysis in order to minimize the occurrence of faults in the scheduling process in advance [16].

At present, the processing of uncertainty factors in dynamic scheduling includes: ① The method that the probability and distribution characteristics of uncertainty factors is known. But the problem of this method is that it cannot accurately reflect the actual situation. The main performance is as follows: Firstly, there are limitations in the coverage of probability and distribution characteristics of uncertainty factors, which affect the applicability of the scheduling model. Secondly, the implementation of uncertainty factors processing with probability and distribution characteristics of uncertainty factors cannot be guaranteed, which makes the accuracy of scheduling model affected. ② The method of data driven. In view of the uncertainty factors that arise, a data-driven approach can be used to form a planning and scheduling plan. However, this method does not consider dealing with uncertainty factors in advance. ③ The method of data prediction. Although the data can be used to preprocess the uncertainty factors in the dynamic scheduling process, it is still worth considering whether the planning and scheduling scheme considering the prediction results can fully guide the actual production. In order to ensure the applicability and accuracy of the scheduling model and the implementation feasibility of the uncertainty factors after preprocess, this paper combines the digital twin technology with the planning and scheduling system to form the planning and scheduling system model based on the digital twin. From before, during, and after production, the comprehensive use of prediction technology, simulation technology, all elements of real-time data acquisition technology. Based on the prediction of the whole production factors, simulation verification and real-time data consistency comparison are used to realize the accurate guidance of the planning and scheduling scheme in the production process.

This paper constructs a scheduling system model based on digital twin. Firstly, the concept of twin workshop is used to integrate the digital twin technology with the planning and scheduling system to form an all-around management and control mechanism of the planning and scheduling system and a digital twin model of the planning and scheduling system. Then, in order to realize the management and control mechanism, the key technologies are elaborated. The method of perception and data collection is combined with the method of Petri net modeling to realize the perception and collection of all elements real-time data. And the prediction of planning and scheduling can be divided into pre-production total factor prediction and production anomalous prediction. Finally, the management and control mechanism is applied to deal with the two uncertainty factors of order change and material change in the process of planning and scheduling, forming a planning and scheduling plan that conforms to the actual production.

## 2 The fusion of digital twin and planning and scheduling systems

### 2.1 The establishment of the management and control mechanism of the planning and scheduling system

In order to ensure that the planning and scheduling scheme can accurately guide the actual production, the following methods are used for management and control. Before production, the uncertainty factors in the production process are dealt with in advance through all factor data prediction and simulation verifications to form a preliminary production planning and scheduling scheme. In the production, the uncertainty factors in the production process are monitored through the consistency comparison of the data during the simulation and the real-time data. In response to the uncertainty factors discovered in time, we adjusted the production plan and scheduling plan again in advance. After production, the above treatment is summarized and a rule base is established to provide theoretical support for the treatment of subsequent uncertainty factors. This mainly involves the collection of real-time data of all production factors, the prediction of all production factor data, the verification of planning and scheduling schemes, the comparison of data consistency, and the formation of planning and scheduling schemes.

Twin workshops using digital twin technology can ensure transparency of workshop information. It is the integration of physical workshop, virtual workshop, information system, and twin data. For planning and scheduling, the virtual workshop can verify the planning and scheduling scheme. Twin data include real-time data of all production factors in physical workshop, simulation data of virtual workshop, etc. The information system here is defined as a production planning system, which can analyze the consistency of data and process the consistency comparison results and data prediction results to form a planning and scheduling scheme. For the prediction of all production factor data, twin data need to be processed in this aspect. The management and control mechanism of planning and scheduling based on twin technology is shown in Fig. 1. It is composed of production planning system, physical workshop, virtual workshop, twin data, total production factor data prediction, and consistency comparison between simulation time data and real-time data.

The management and control mechanism is divided into small cycles and large cycles:

1. Small cycle: ① the planning and scheduling scheme formed by the production planning system is transmitted to the virtual workshop for simulation verification, and the simulation verification results are transmitted to the production planning system. If the results are feasible, it will be directly transmitted to the physical workshop to

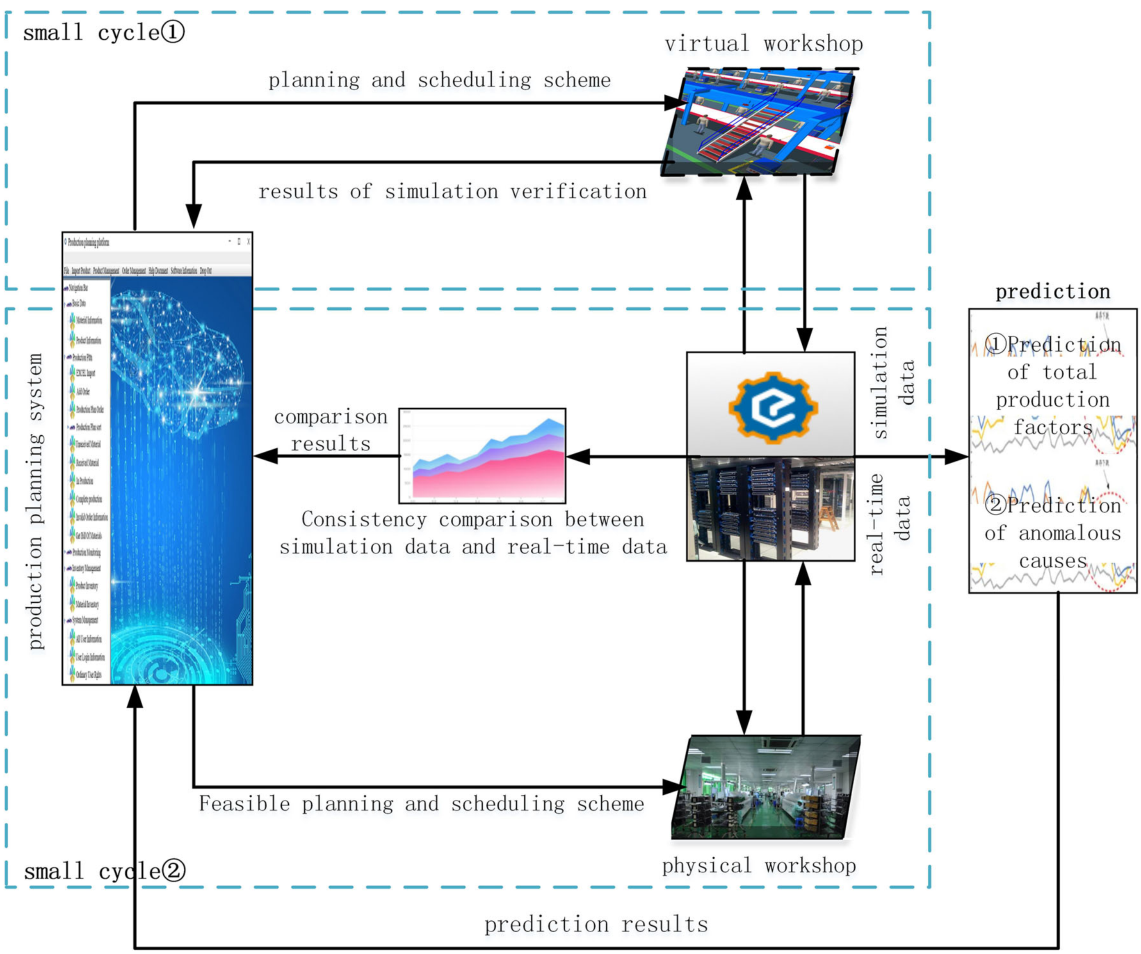


**Fig. 1** Management and control mechanism of planning and scheduling system based on digital twin.pdf

guide production. Otherwise, the scheme is rescheduled and then transmitted to the physical workshop to the physics workshop in the production planning system. ② When the physical workshop carries out the feasible preliminary planning and scheduling scheme, it is carried out in the way of rolling scheduling. In the rolling process, the consistency between the workshop data of the planning and scheduling scheme during simulation and the real-time workshop data is compared to realize the monitoring of uncertainty factors in the production process. If the comparison data is consistent, it will be executed according to the scheduling scheme. If it is inconsistent and beyond the normal range, it will be rescheduled to form a new scheduling scheme.

2. Large cycle: ① Prediction of total production factors. Twin data is used to predict the total factors of production, and the possible uncertainty factors are predicted. If the predicted value is within the normal range, proceed according to the planning and scheduling scheme. Otherwise, the predicted uncertainty factors will be fed back to the production planning system, which will reschedule according to the specific situation. ② Prediction of anomalous causes. The twin data is used to predict the anomaly and find the cause of the anomaly so as to recover the anomaly in time. The production planning system can arrange the planning and scheduling scheme according to the specific situation of anomalous recovery.

Combining the large cycle and the small cycle, an all-around description of the management and control mechanism of the planning and scheduling system based on digital twins is as follows.

1. Before production, it is a comprehensive use of small cycle ① and large cycle ①. When the plant-level daily production plan is transferred to the production planning system, the production planning system will schedule the daily production plan according to the prediction results of the total production factors to form the preliminary planning and scheduling scheme including the product sequence and quantity. After the formation of the preliminary planning and scheduling scheme, the virtual workshop coordinates the relevant resources of the physical workshop to carry out simulation verification according to the relevant contents in the standard operation procedure (SOP). If the simulation is correct, the simulation verification results will be fed back to the production planning system. If there is any error, the production planning system will reschedule and simulate again. For SOP, if the products in the preliminary planning and scheduling scheme have been produced, the contents in SOP will be directly called for simulation and verification. If it has not been produced, it is necessary to form SOP through the following operations. First, determine the technology process and determine the time of each process according to the similarity of the process. Then, the production line balance is taken as the goal to divide the work units, so that the production line balance rate is good. Finally, operation instructions for each process are formed. The detailed process is shown in Fig. 2.
2. In production, it is the comprehensive use of small cycle ①, ② and large cycle ②. The production planning system will transfer the preliminary planning and scheduling scheme that is formed before production to the physical workshop. The physical workshop makes rolling scheduling in the production process. The virtual workshop is simulated to verify the feasibility of the planning and scheduling scheme in the next 8 h. If the scheme is feasible, lock the scheme of the earlier 2 h. Otherwise, predict the cause of simulation anomaly, reschedule the scheme, and then lock the scheme of the earlier 2 h. Feedback the locked scheme to the physical workshop 2 h in advance. In the implementation of the locked scheme, the uncertainty factors are monitored. The consistency between the simulation data and the real-time data is compared. If the data is inconsistent and beyond the normal range, the production planning system needs to be rescheduled, and the scheduling results are fed back to the virtual workshop for simulation verification. Otherwise, according to the simulation verification, feedback scheme to continue. The detailed process is shown in Fig. 3.
3. After production, analyze and archive the twin data of the workshop before and during production. Analyze historical data of the production plan to find out the cause of the change in the production plan and establish a corresponding rule base. It provides support for the adjustment of the workshop information system model or the formulation of future production plans.

## 2.2 Digital twin model construction of the planning and scheduling system

In order to realize the management and control of planning and scheduling system, we need to build a digital twin model of the planning and scheduling system. Combined with the composition of digital twin workshop and the management and control mechanism of the planning and scheduling system, the digital twin model of the planning and scheduling system is mainly composed of the following five parts: physical workshop, virtual workshop, digital twin platform, data prediction, and production planning system. The twin data is mainly used for data prediction, and the production planning system includes data consistency analysis. The specific structure is shown in Fig. 4. It builds virtual

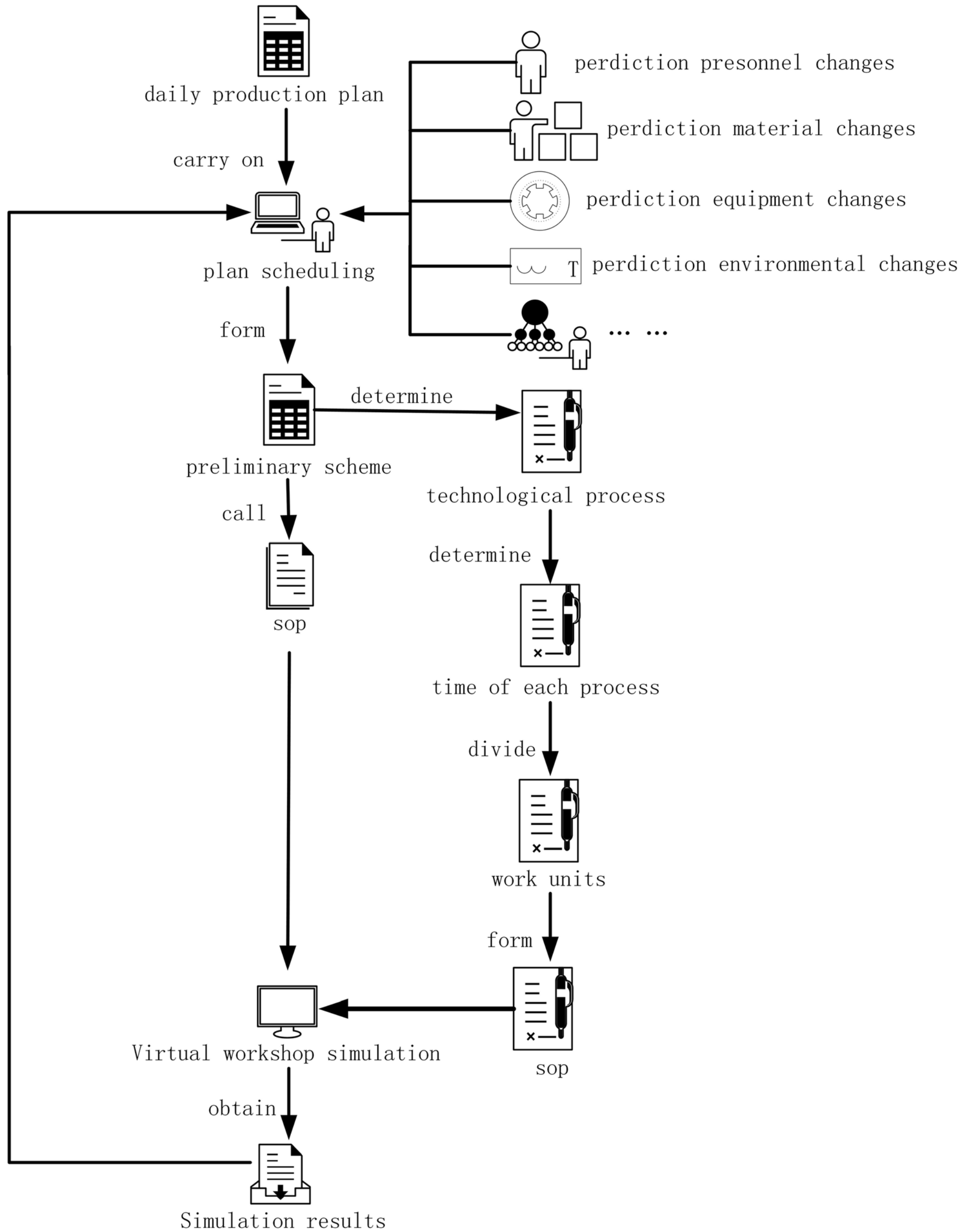


**Fig. 2** Management and control mechanism before production

workshop and workshop twin data platform around physical workshop and uses twin data to predict and analyze consistency and processing, and finally forms a production planning and scheduling system conforming to the actual situation of the enterprise.

**Physical workshop** The physical workshop is a collection of existing physical workshop entities, including production lines, production-related personnel, equipment, materials, and so on, and primarily responsible for planning the production of required products. The physical workshop can be divided into three levels: the unit layer, the system layer, and the complex system layer. The unit layer refers to the static production factors of the production workshop, which is generally composed of the equipment and layout of the production line, workshop temperature, humidity, and so on. The system layer refers to the addition of factors related to production activities on the basis of the unit layer. It is generally composed of product processes related to the production process, operation of materials, personnel, and equipment between processes. The complex system layer refers to the addition of raw materials and finished products on the basis of the system layer.

**Virtual workshop** The virtual workshop is digital mirroring and virtual reconstruction of entity activity of the physical

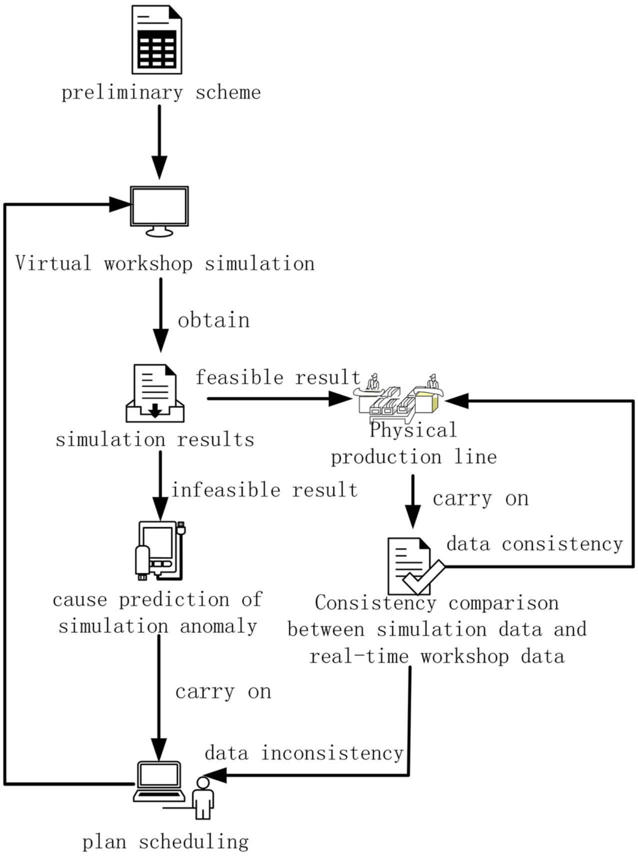


**Fig. 3** Management and control mechanism in production

workshop through modeling technology. The virtual workshop is established according to the physical workshop, which is composed of the virtual model of the unit layer, the system layer, and the complex system layer. The unit layer refers to using of three-dimensional modeling tools such as Demo 3D, Auto CAD, and Solid Works etc. to establish a three-dimensional model of the workshop's static production factors. System layer means that on the basis of the unit layer, the data related to the production process is written into the unit layer model so that the virtual workshop can simulate the production activities. Complex system layer refers to the distribution of raw materials and the storage of finished products on the basis of the system layer into the simulation model to achieve a comprehensive evaluation and verification of the full range of simulation and production activities of the workshop activities.

The data between the virtual workshop and the physical workshop is mapped and interacted between layers (unit layer, system layer, complex system layer), and the machine learning method is used in the process of mapping and interaction to iteratively optimize the virtual model. In the physical workshop, sensors, RFID, and other sensing devices are used to collect multi-source heterogeneous data and establish the corresponding data model. In the virtual workshop, plug-in development is carried out with the established model as the carrier to assist the creation of the production information model to realize the real-time mapping and interaction between the physical workshop and the virtual workshop. Unit layer uses workshop physical data model and simulation software to establish a virtual workshop geometry model. The system layer is the basis of the unit layer to map and interact with the production process information. The complex system layer is based on the system layer to coordinate raw material distribution information, finished product storage information to realize real-time mapping and interaction between the physical workshop and the virtual workshop.

**Digital twin platform** The primary role of the twin data platform is to store relevant data. When data information is required, you only need to make a call on this platform. The data here mainly include physical workshop data, virtual workshop data, workshop interaction data, scheduling data, and so on. Among them, the physical workshop data mainly includes the full production factor data and production process data. Virtual workshop data is mainly the data after the simulation of the virtual workshop. Workshop interaction data is the data generated by the interaction of the virtual and physical workshops at the unit layer, system layer, and complex system layer. These data can realize the complete mapping of the physical workshop and the virtual workshop. Scheduling data is scheduling-related data generated by combining the production plan and the real-time data, virtual workshop data, and workshop interaction data during the planning and scheduling process.

**Data prediction** When making data prediction, you need to call the data in the twin data platform, and use the common methods of data prediction to analyze and process the data to achieve the prediction of uncertain factors. Using the real-time data of production equipment to make accurate prediction of equipment availability can reduce the impact of equipment failure on production scheduling. Using the real-time data of production plan, making accurate prediction of the change of production plan can reduce the impact of the planned change on the production scheduling. Using the real-time data of personnel to make accurate prediction of personnel changes can reduce the impact of personnel attendance, skills, and so on in the aspect of production scheduling. Using the real-time data of the material to make accurate prediction of the material change can reduce the impact of material quality, quantity, and so on in the aspect of the production schedule. In addition, real-time data can be used for other forecasts, such as the change of delivery time. These forecasts are fed back into the production planning system to provide a basis for the rescheduling of the production plan.

**Production planning system** The production planning system is the real-time scheduling of the production plan according to the state information of the manufacturing resources in the

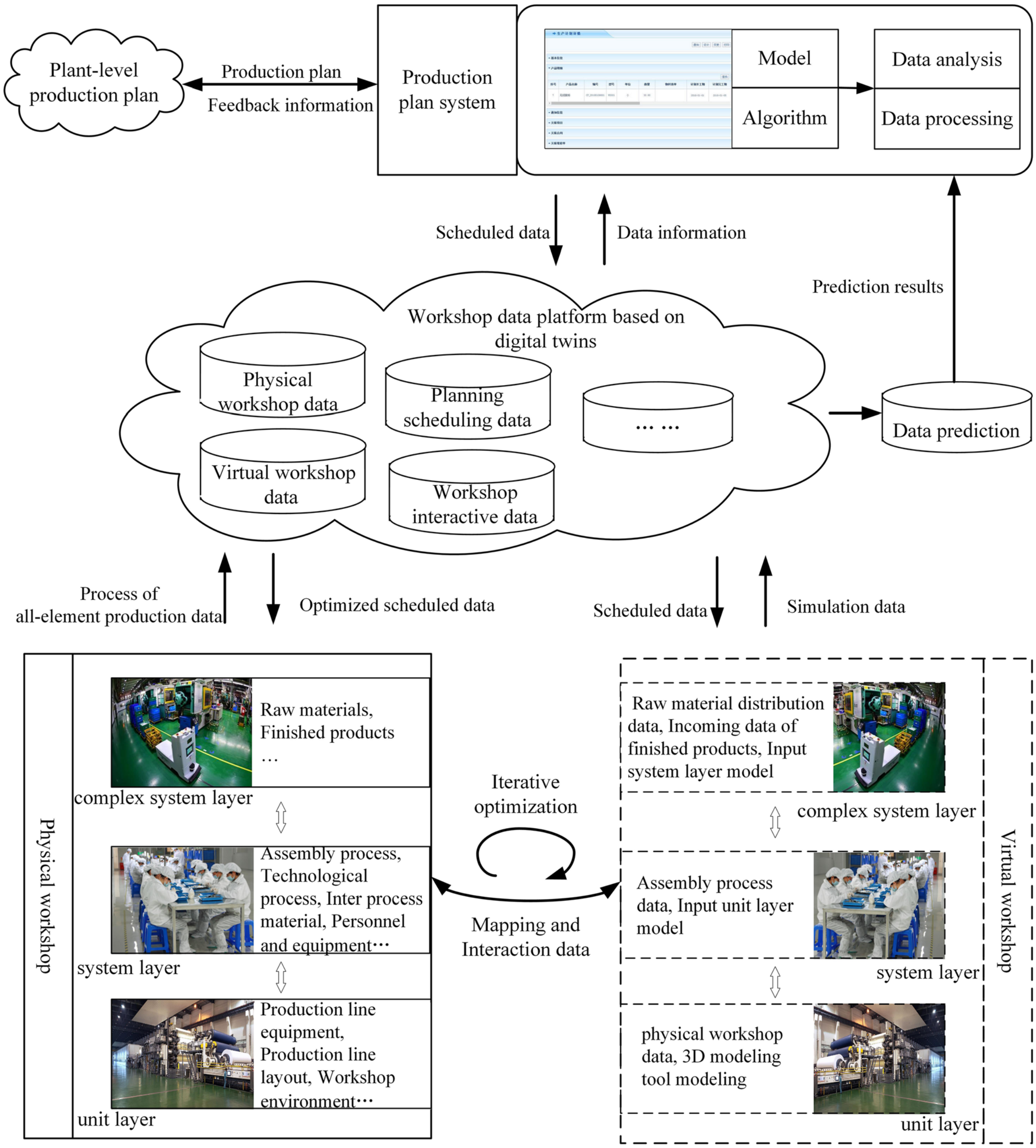


**Fig. 4** Digital twin model of the planning and scheduling system

production workshop. The plan data, plan-related twin data, and predictive data are transferred to the production planning system containing models and algorithms for data consistency analysis and processing. The processed data is transmitted to twin data platform, which then transmits the processed data to virtual workshop for simulation. The simulation is error-free and then transmitted to the physical workshop through the production planning system. The physical workshop transfers the scheme level by level according to the hierarchical relationship of the workshop, which is from the complex system level to the system level and finally to the unit level.

## 3 Key technologies of planning and scheduling system based on digital twin

The key technology of planning and scheduling system based on digital twin mainly includes the following two major aspects. The perception and collection of all-factor information mainly describes the common methods of perception and data collection and how to apply this method at different levels of the workshop to achieve active perception of total production factors, planning scheduling forecast before and during production.

## 3.1 The perception and collection of all-element information

### 3.1.1 Awareness and data collection methods

Typically, the data to be perceived and collected is real-time data of people, machines, materials, method, and environment associated with production activities. This data plays an important role in planning and scheduling. The acquisition of these real-time data can be obtained through the technology of RFID, image recognition, and so on; the tools of plc, microcontrollers, and so on; sensor devices, the management systems of databases, planning systems, and so on; the means of manual measurement etc. However, in the process of data perception and acquisition, their interface protocols are different because of the different technologies and equipment manufacturers, which make multi-source heterogeneous data more difficult to collect. In this regard, there is an established unified standardized communication framework. With the development of embedded, different data, acquisition sources are integrated into heterogeneous groups and connected to the industrial controller to form a perceptive device for embedded multi-source manufacturing information [17], as shown in Fig. 5.

The display terminal is used to visualize the data obtained at the underlying level. The industrial control machine is used to deploy and operate the software system required for multi-source manufacturing information awareness to centrally manage sensor nodes that capture multi-source manufacturing and encapsulate multi-source manufacturing information-aware push and remote services. The heterogeneous interface integrator is used to integrate a variety of heterogeneous interface terminals, enabling the underlying data acquisition source, communication module, display terminal and the connection and communication of the industrial control machine. Standardized communication architecture can realize the plug-and-play interface of the underlying data acquisition source and realize the timely acquisition of data.

### 3.1.2 Application of perception and data collection on the workshop

**The unit layer** The data of production line equipment mainly refers to the original data of the equipment, which is obtained by the production instruction. The data of the production line layout mainly refers to the data related to the physical production line layout and be obtained by manual measurement. The production environment data is obtained by temperature and humidity meter.

The system layer is mainly to perceive and collect the real-time data in the production process. In order to obtain the real-time data, the Petri network modeling method is used to describe the logical behavior in the production process. Then, in order to perceive the real-time change of logical behavior, the corresponding data acquisition device is configured to achieve the purpose of real-time data acquisition [18]. The logical behavior relationship described by the Petri network is shown in Fig. 6. A description of its production process is shown in Table 1.

In the figures, $s_1$, $s_2$, $s_3$, $s_4$, $s_5$, $s_6$ are decision points, the rules for the change of these two process: When the work pieces arranged in the scheduling scheme enter the first process of production, there are $e_1$ and $m_1$ tokens in the $f_1$ and $w_1$ libraries, that is, when the equipment and people are idle, $T_{11}$ is triggered in real time according to the rules of decision point $s_1$, so that the work piece is processed in the first process. After

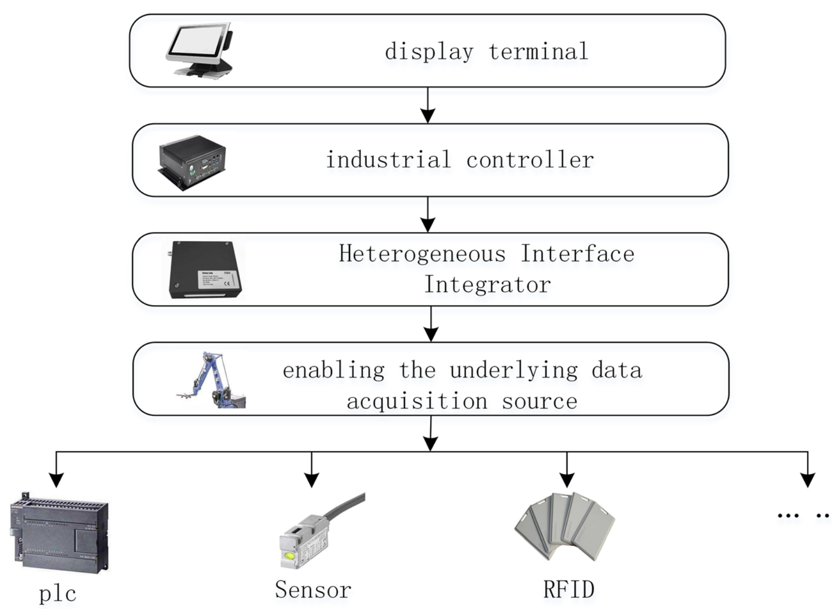


**Fig. 5** Standardized communication framework

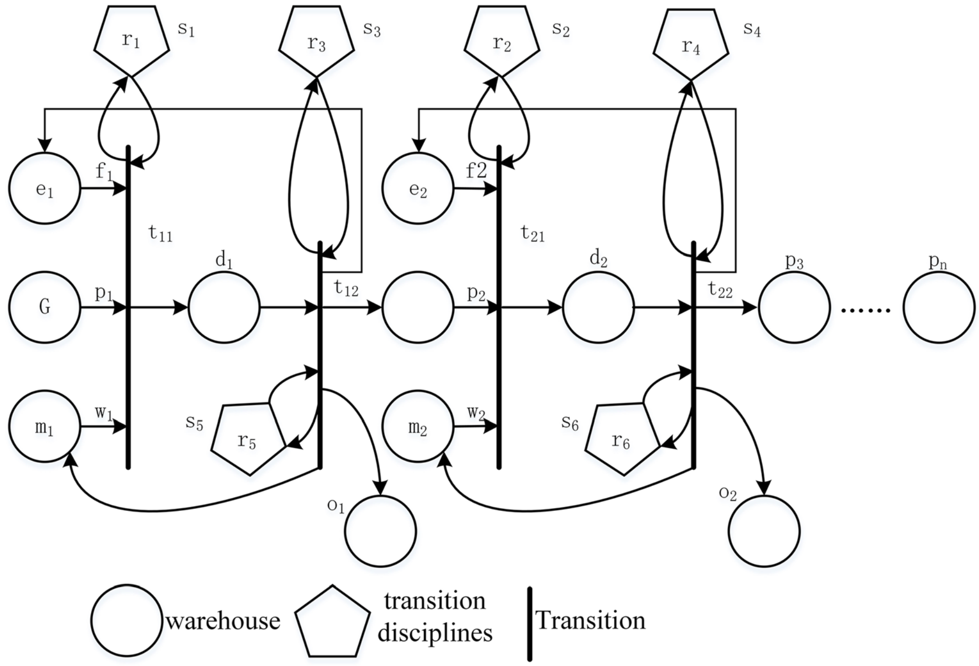


**Fig. 6** Logical behavioral relationships described by the network of petri

the work piece is processed in the first process, it will be carried out in two parts. In the first part, the rule of decision point $s_3$ triggers $t_{12}$ in real time to return the workpiece and the equipment to the original $f_1$ and $w_1$ library, that is, the first process of the work piece and equipment after the completion of the operation in the idle state. In the second part, the rule of decision point $s_5$ will decide whether to enter the output buffer of $o_2$ or $p_2$ after the first operation is finished. By analogy, all subsequent processing procedures are also similar. The entire process is completed until the last process is completed, and all the work pieces are entered into the buffer waiting library of $p_n$.

The complex system layer involved raw material distribution information and production planning information access. For raw material information, the raw materials and the container carrying the raw materials are equipped with electronic tags. The real-time status information and finished product storage information can be collected by an RFID reader. The scheduling information is obtained through the twin database platform.

**Table 1** Description of the production process

| Alphabet | Meaning |
|---|---|
| $e_1$, $e_2$ | Equipment that represents respectively the first and second operations |
| $m_1$, $m_2$ | Workers representing the first and second operations, respectively |
| $G$ | Part (raw material) that represents the product in the first operation |
| $f_1$, $f_2$ | Indicates the completion of the first and second processes, respectively. |
| $p_1$, $p_2$, $p_3$ | The work piece (work in work) of the first, second, and third processes, respectively, is entered buffer waiting library |
| $p_n$ | The work piece (finished product) that represents the last operation is fed buffer waiting for the library |
| $d_1$, $d_2$ | Indicates that the work piece is being processed in the first and second operations, respectively |
| $o_1$, $o_2$ | The output cache is indicated separately after the work piece has been processed |
| $t_{11}$, $t_{21}$ | Indicates respectively that the first and second processes begin processing |
| $t_{12}$, $t_{22}$ | Indicates the completion of the first and second processes, respectively. |
| $s_1$, $s_2$, $s_3$, $s_4$ | The rules of occurrence that represent change |
| $s_5$, $s_6$ | Represents the changed output rules separately |

### 3.2 Prediction of planned scheduling

Prediction refers to the use of existing knowledge, experience, and scientific methods to estimate the future environment and to estimate and evaluate the future development trend of things based on known factors in the past and present [19]. The predictions in planning and scheduling are mainly divided into two categories, namely, prediction before production and prediction in production.

Prediction before production refers to prediction of total production factors. It mainly uses historical big data related to production factors in the twin data platform to make predictions, such as quality data prediction, production capacity prediction, abnormal loss time prediction, etc. Common prediction methods include qualitative prediction and quantitative prediction. Among them, qualitative prediction includes expert meeting method, Delphi method, etc. and quantitative prediction includes moving average, exponential smoothing, Box-Jenkins method, Markov method, gray system model, proportional hazard model, state space model, neural network prediction method, etc.

Prediction in production refers to prediction of anomalous causes. The abnormal events in the production process are obtained through simulation, and the reasons for the abnormal occurrence are obtained through analysis. By analyzing historical data, a decision analysis rule base is established. The abnormal events in the virtual workshop simulation are matched with the decision analysis rule base, and the abnormal events are extracted and identified. For the identified abnormal events, according to the product ID and performance type, call out relevant abnormal cause location classification rules, and match with actual conditions to screen out possible exceptions.

## 4 Case

The constructed model is applied to the frame workshop to solve the problem that the uncertain factors of the current frame workshop cannot be handled in time in the planning and scheduling process. The upstream customer assembly shop has placed production orders for it, and the downstream customer material workshop provides them with materials. When there are uncertain changes in the order of the assembly shop and the materials in the material workshop, these changes cannot be timely feedback in the decision-making process of the planning and scheduling, which seriously affects the accuracy of the scheduling results. According to the current planning and scheduling characteristics of the frame workshop, changes in orders can be obtained from the assembly shop one afternoon before production, which will not affect normal production, but material changes during the production process cannot be obtained. In addition to this workshop's production planning information cannot communicate with logistics in real time. The specific performance: Question 1, manual scheduling information cannot be communicated with real-time information of the physical production line. Question 2, in the process of material selection, the material picking information and the real-time information of the material plant materials cannot be communicated. Question 3, in the process of replenishing missing materials, the information of missing materials and the distribution method of missing materials cannot be communicated in real time.

In order to solve the problems existing in the planning and scheduling process of the frame workshop, a planning and scheduling management and control mechanism based on digital twin technology is used to obtain the material changes in the production process on time, and the feasible planning and scheduling scheme is transmitted to the physical workshop. The digital twin model of the planning and scheduling system is used to realize the fusion of information flow and logistics. And on this basis, the scheduling model is established to realize the timely processing of uncertainty factors. To this end, an improvement plan is proposed. First, analyze and optimize the scheduling process to achieve timely acquisition of material changes, and the fusion of information flow and logistics. Then, establish a planning and scheduling system that complies with the workshop to realize the timely treatment of uncertain factors. Finally, carry out the implementation of the planning and scheduling system.

### 4.1 Scheduling process analysis and optimization

#### 4.1.1 Analysis of scheduling process

The scheduling process of the frame workshop can be described as the manual scheduling results transmitted to the storage system of the material workshop through the MES system every 2 h. In the storage system, the materials required for dispatch are issued, and the picker allocates according to the order information, and then performs material distribution. The planner checks the delivered materials and sends them to the frame workshop for production after checking. If there are any errors, the planner will return them to the material workshop, and the planner will reschedule manually. In this process, when the picking is wrong, the picking is stopped, causing waste in the picking process; when there is a shortage of materials, all the materials are returned to the warehouse, causing waste in the transportation process; after the return, the production is manually scheduled, which causes waiting for waste. This makes the real-time interoperability of information flow and logistics poor, and scheduling efficiency is low.

#### 4.1.2 Scheduling scheme optimization

First, establish a rolling scheduling plan mode, match the material information based on the material information at the time of storage and the materials required for the scheduling plan, and check the material changes of the planned scheduling plan in the next 8 h. Consider whether to reschedule and lock the plan for the first 2 h according to the material changes. Send the locked planning and scheduling scheme and required material information to the production department of the frame workshop and the material workshop 2 h in advance.

Secondly, it is necessary to obtain real-time information of the production process to realize the fusion of information flow and logistics. Improve the manual production scheduling method, establish a planning and scheduling system, and connect the system with MES to achieve the fusion of scheduling information and real-time information of the physical production line. Improve the material selection problem, optimize the scheduling process in combination with the rolling scheduling plan mode, and realize the integration between the material selection information and the materials in the material plant. Improve the problem of shortage of materials, change the way of replenishment, and achieve the integration between the information of the shortage of materials and the distribution of missing materials.

Finally, optimize the scheduling process. The optimized scheduling process is shown in Fig. 7. The material information at the time of material storage and order information are sent to the frame plant scheduling system through the MES system. In the planning and scheduling system, carry out scheduling and check the materials required for the scheduling scheme. After the check is correct, the information of the materials that match the plan is transmitted to the material plant. The picker selects the material, and the material is sent to the frame and pulled into the production department for verification. The planner will check, and the materials will be sent to the frame workshop production department for production after checking. If there is an error, the material plant

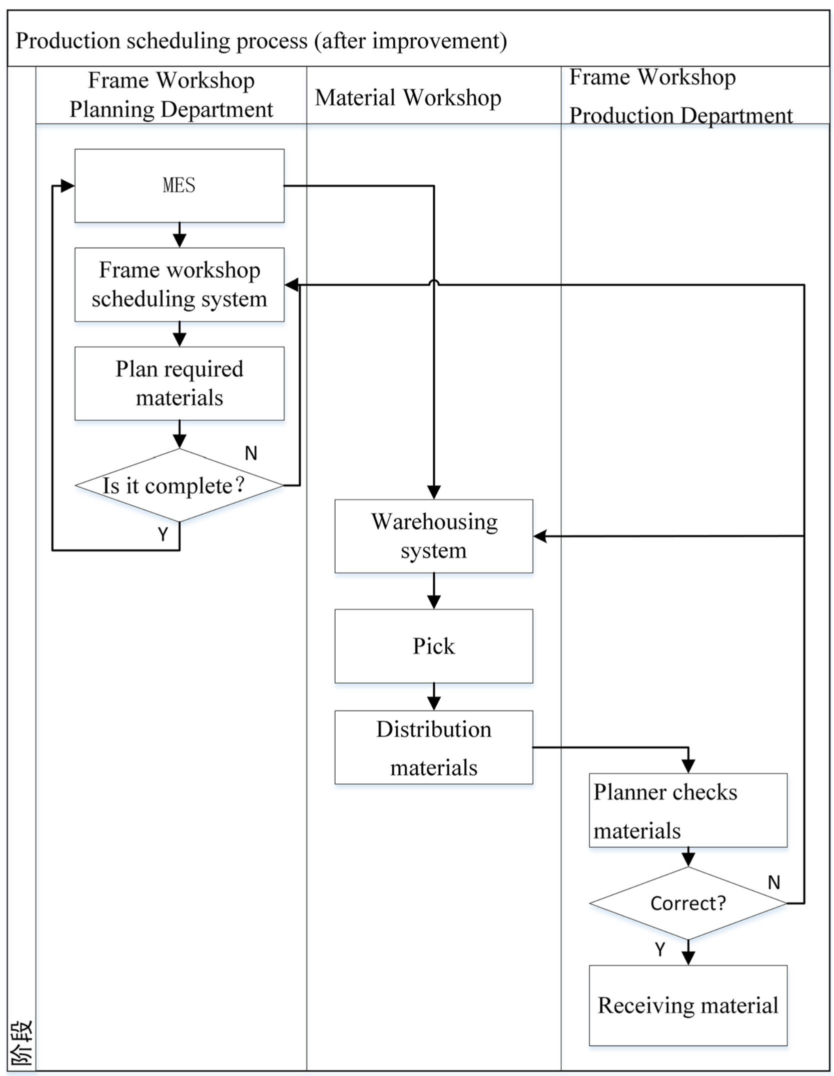


**Fig. 7** Scheduling process (after optimization)

will replenish according to the received replenishment information, and the frame workshop scheduling system will reschedule production.

## 4.2 Establishment of planning and scheduling system

### 4.2.1 Establishment model

Combined with the improved scheduling process, to design an intelligent scheduling system, it is required to be able to process the information of materials and orders in real time. Due to the limitation of the rated working time during the scheduling process, the capacity is limited. When the production line balance rate reaches 93%, it is known that the takt time of model $A$ is $Tt_A = 160$S, the takt time of model $B$ is $Tt_B = 167$S, and the takt time of model $C$ is $Tt_C = 156$S. With a known takt time, ordering a fixed order gives the estimated delivery time for the order. Therefore, based on the consideration of order conditions, material conditions, capacity constraints, and estimated delivery time, a planning and scheduling model with the goal of minimizing total loss costs is established.

Before mathematically modeling the scheduling method, make the following assumptions about the sequencing problem studied: ① The total time to produce the first product is the cycle time, and the total time to produce the remaining products is the takt time. ② Take the maximum takt time of the three models as the tact time in the sequencing model. ③ Changes in production personnel will not affect production on the production line.

The scheduling problem can be described as if the main plant requires completion of product $i$ within the delivery period $TD_i$, product $i$ is completed at the corresponding location $j$. There are $n$ products, $y$ positions, and $z$ products actually produced. Product $i$ is based on the number of parts $k_i$ required by the BOM. $qi$ is the actual number of parts corresponding to product $y$ in the material plant. Generally speaking, the rated working time $T$ of a worker is 16 h. If the rated working time is exceeded, the maximum overtime $H$ is 2 h, $h$ is the actual overtime of the worker, the overtime cost per hour is $c$, the number of overtime is $P$, and $hpc$ is overtime cost; $m$ is the first product that exceeds the maximum capacity without considering overtime when sorted by delivery date. The $j$ position has a fixed estimated delivery time. Take $t_{ij}$ as the estimated delivery time of product $i$ at $j$ position and $T_t$ as the tact time. When product $i$ is delayed, the total loss cost is $f$, and the penalty factor is . $\partial\frac{t_{yz}}{TD_y}$ represents a penalty fee for non-delivery. The mathematical model of the problem is described as follows:

$$\min f = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\partial\frac{t_{ij}}{TD_i} + hpc\right)x_{ij} \quad (1)$$

$$\sum_{i=1}^{n} k_i x_{ij} \le \sum_{i=1}^{n} q_i \ (j = 1, 2, \ldots, y) \quad (2)$$

$$\sum_{i=1}^{n} x_{ij} - \frac{T}{T_t} > 0 \ (j = 1, 2, \ldots, y) \quad (3)$$

$$hpc \le \sum_{i=m}^{n} \partial_i \frac{t_{ij}}{TD_i} \quad (4)$$

$$h \le H \quad (5)$$

$$\sum_{i=1}^{q} x_{ij} \le \frac{T + h}{Tt} \quad (j = 1, 2, \ldots, z) \quad (6)$$

$$\sum_{i=1}^{q} x_{ij} = 1 \quad (j = 1, 2, \ldots, z) \quad (7)$$

$$\sum_{j=1}^{q} x_{ij} = 1 \quad (j = 1, 2, \ldots, z) \quad (8)$$

$$x_{ij} = 0, 1 \quad (9)$$

Equation (1) represents the optimization goal, and the goal is to minimize the total loss cost. Equation (2) indicates that the actual number of parts of the product is not less than the number of parts required for the planned product. Formula (3) indicates that the number of existing products exceeds the maximum capacity quantity formula without considering overtime. Equation (4) indicates that when the penalty cost is greater than or equal to the overtime cost, the worker actually works overtime. Equation (5) indicates that the actual overtime hours of the workers do not exceed the maximum overtime hours. Formula (6) represents the maximum capacity formula including the actual overtime of the worker. Equation (7) indicates that only one position can be arranged for each product. Equation (8) indicates that only one product can be arranged at each position. Equation (9) indicates that the final result can only be 0 or 1.

### 4.2.2 Production status establishment

The production status can generally be divided into four categories: no material has been received, material has been received, production is in progress, and production has been completed. Combined with the actual situation of the frame plant, the status of the order and material changes is analyzed. Because the order change is made only before production, the order change is in the state of no picking material. It can be known from the optimized scheduling process that material changes may occur in the planned unpicked or picked status. Different countermeasures are taken for the status of the order. The order is subject to changes in the order itself or material changes in the uncollected state and only needs to be rescheduled using the scheduling system. Orders are subject to material changes in the state of picking. Not only must the production be rescheduled based on the material's pre-arrival time, but the material plan must be notified for replenishment.

**Table 2** Initial order information

| Order number | Order status | Quantity A | Quantity B | Quantity C | Customer name | Order time | Delivery time |
|---|---|---|---|---|---|---|---|
| D10003 | Unpicked | 40 | 72 | 39 | Customer 3 | 11–15 08:00 | 11–19 15:30 |
| D10004 | Unpicked | 79 | 46 | 50 | Customer 4 | 11–15 14:00 | 11–19 09:10 |
| D10005 | Unpicked | 52 | 53 | 55 | Customer 5 | 11–16 08:00 | 11–20 02:00 |
| D10006 | Unpicked | 28 | 78 | 56 | Customer 6 | 11–16 14:00 | 11–19 22:30 |
| D10007 | Unpicked | 57 | 59 | 80 | Customer 7 | 11–17 08:00 | 11–19 12:00 |
| D10008 | Unpicked | 50 | 63 | 67 | Customer 8 | 11–17 14:00 | 11–20 08:20 |
| D10015 | Unpicked | 31 | 44 | 50 | Customer 15 | 11–17 16:00 | 11–19 16:00 |
| D10019 | Unpicked | 50 | 67 | 61 | Customer 12 | 11–17 14:00 | 11–19 10:50 |

### 4.3 Implementation of the planning and scheduling system

Design the scheduling system. The planning and scheduling system is divided into three layers: the application layer, the business layer, and the data layer. Combining the planning and scheduling model, the production state of uncertain factors, and the solution method of the rule model, a planning and scheduling system capable of real-time feedback and update of production data is designed. The system is connected with the MES of the workshop to realize the timely feedback of material change information and the timely processing of orders and material changes.

Take the typical order change situation as an example to implement the planning and scheduling system. The initial order information is shown in Table 2. Now, the order information of customer 12 needs to be inserted, and the system performs scheduling.

The scheduling results finally planned by the frame plant scheduling system are shown in Table 3. It is feasible to combine the real production situation.

**Table 3** Scheduling results

| Order number | Order status | Quantity A | Quantity B | Quantity C | Customer name | Order time | Delivery time |
|---|---|---|---|---|---|---|---|
| D10004 | Unpicked | 79 | 46 | 50 | Customer 4 | 11–15 14:00 | 11–19 09:10 |
| D10019 | Unpicked | 50 | 67 | 61 | Customer 12 | 11–17 14:00 | 11–19 10:50 |
| D10007 | Unpicked | 57 | 59 | 80 | Customer 7 | 11–17 08:00 | 11–19 12:00 |
| D10003 | Unpicked | 40 | 72 | 39 | Customer 3 | 11–15 08:00 | 11–19 15:30 |
| D10015 | Unpicked | 31 | 44 | 50 | Customer 15 | 11–17 16:00 | 11–19 16:00 |
| D10006 | Unpicked | 28 | 78 | 56 | Customer 6 | 11–16 14:00 | 11–19 22:30 |
| D10005 | Unpicked | 52 | 53 | 55 | Customer 5 | 11–16 08:00 | 11–20 02:00 |
| D10008 | Unpicked | 50 | 63 | 67 | Customer 8 | 11–17 14:00 | 11–20 08:20 |

### 4.4 Comparison before and after improvement

The unit month is used here for comparison before and after improvement. The response time between the manual scheduling information and the physical production line was reduced from 5400 to 900 min, which is a reduction of 83.3%.The response time between the material picking information and the real-time information of materials in material factory was reduced from 4575 to 1600 min, which is a reduction of 65.0%.The response time between the lack of material information and the distribution of missing materials was reduced from 600 to 60 min, which is a reduction of a 90.0%.

## 5 Conclusions and outlook

The planning and scheduling system based on digital twins analyzes the all-around management and control method to realize the uncertainty factors of the workshop using digital twins. It designs the digital twin model of the planning and scheduling system. It elaborates the methods of perception and collection of the full-factor information of different layers of data in the workshop and the prediction methods of planning and scheduling before and during production. These provide design methods and implementation ideas for the real-time dynamic scheduling system of the workshop. Through the scheduling case of the frame plant, real-time feedback and timely processing of the two uncertain factors of orders and materials are realized, which provides a practical basis for implementing a digital twin-based scheduling system for workshop planning. However, there are still many uncertain factors in the production process, such as equipment failure and absence of personnel. In the subsequent research process, it is necessary to combine the digital twin-based workshop planning and scheduling system to achieve the timely processing of more uncertain factors, so that the planning and scheduling system is more complete.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

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