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Industry 4.0-Oriented Turnkey Project: Rapid Configuration and Intelligent Operation of Manufacturing Systems

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Abstract: More extensive personalized product requirements and shorter product life cycles have put forward higher requirements for the rapid establishment, commissioning, and operation of corresponding manufacturing systems. However, the traditional manufacturing system development process is complicated, resulting in a longer delivery time. Many manufacturing enterprises, especially small and micro enterprises, may not have the necessary manufacturing knowledge or capabilities to meet these requirements. Therefore, it is essential to promote the construction of turnkey projects under the paradigm of Industry 4.0, parallelizing and integrating the existing manufacturing system development process based on mass manufacturing equipment to quickly provide turnkey solutions for manufacturing systems' configuration and implementation for these enterprises. This paper aims to extract and refine the configuration and operation key views of the Industry 4.0-oriented Turnkey Project (I4TP) from Reference Architecture Model Industrie 4.0 (RAMI4.0) and use it to guide the development of key functional processes of turnkey projects to achieve rapid configuration and efficient operation management of manufacturing systems. The turnkey project platform in the Advanced Manufacturing Technology Center (AMTC) is taken as a demonstration case to provide a reference idea for the rapid configuration and intelligent operation of the turnkey manufacturing system.

Keywords: industry 4.0; turnkey project; manufacturing system configuration; manufacturing system operation; key enabling tools

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1. Introduction

In the context of Industry 4.0, as people's demands for personalized products increase and the acceleration of consumer demands changes, the speed of product upgrades is accelerating, and product life cycles are becoming shorter and shorter. What's more, the batch size of a single product is also corresponding to decreases [1,2]. Manufacturing companies are required to reduce the time of product development and manufacturing systems from set-up to operation as much as possible, realize the rapid reconfiguration of the manufacturing systems according to orders to adapt to new production tasks, and save costs. However, new manufacturing systems' traditional sequential development processes make the delivery time longer and they cannot catch up with current market changes. With the continuous development of globalization, manufacturing equipment has become abundant, and the development of manufacturing systems has gradually transformed into selecting manufacturing equipment and combining them to form a manufacturing system.

The continuously evolving computer-aided technologies, as well as the emerging ICTs (Information and Communications Technologies), such as the Internet of Things (IoT), cloud computing, mobile internet, Artificial Intelligence (AI), and so on, provide technical support for intelligent manufacturing to a large extent, including efficient product engineering and manufacturing [3]. Although engineers can use these technologies to address the challenges of the rapid development of products and the quick response of manufacturing systems, how to effectively integrate these technologies to realize the application in actual production is a problem faced by many manufacturing companies. At the same time, many manufacturing companies, especially small and micro enterprises, have certain product innovation and development capabilities but may lack the necessary knowledge or ability to plan and integrate appropriate manufacturing systems to respond to market demands [4].

Therefore, it is essential to build a turnkey project to provide turnkey services in response to market changes and manufacturing companies' turnkey needs for manufacturing systems. ICTs are comprehensively used to parallel and integrate manufacturing system development processes. Under various constraints such as cost, quality, delivery time, and batch size, a manufacturing system that quickly meets the product needs of the market is developed based on the existing manufacturing equipment, and the intelligent operation management of the manufacturing system is realized. It provides manufacturers with a turnkey solution and enables them to quickly establish or adjust manufacturing systems and successfully put them into operation according to product orders.

The construction of the Industry 4.0-oriented Turnkey Project (I4TP) involves numerous factors, such as business, assets, information, and functions under the Industry 4.0 paradigm. In the theoretical research aspect, the Reference Architecture Model Industrie 4.0 (RAMI4.0) [5] aims to create digital description rules for technical objects throughout their life cycle and related value changes and defines detailed concepts, standards, and interactions. However, there is no detailed description of the implementation and application process for specific fields, including turnkey projects [6], and there is no subdivision architecture based on RAMI4.0 to guide the formation, commissioning, and operation of manufacturing systems. Regarding the application aspect, the rapidly emerging smart factories around the world, such as Fast Radius' Cloud Manufacturing Platform [7], Phoenix Contact's Digital Factory [8], Rold's SMARTFAB [9], and some other cases [10,11], have the capability of autonomous overall management, able to carry out systematic coordination, reorganization, and expansion to provide specific solutions for product production. Although the smart factory can provide various support for the turnkey project and even expand the business service scope, it still cannot fully satisfy the core functional requirements in the whole process of the turnkey project from product to manufacturing system configuration and operation.

To cope with the above problems, the views of two core functional processes are proposed in this paper focused on the set-up, commissioning, and operation process to guide the construction of I4TP. The I4TP's characteristics, transforming the development of manufacturing systems into configuration processes and carrying out the efficient intelligent operation management to the manufacturing system, are considered in these views. The specific implementation of the turnkey project is explained with a demonstration case. The main contributions of this paper are as follows:

- In response to the growing demand for turnkey services of manufacturing systems under the trend of personalized manufacturing, key research on the configuration and operation of manufacturing systems is carried out around the construction and implementation of I4TP;
- Through the introduction of the I4TP, the core functional process of it is summarized into the configuration and the operation management of manufacturing systems, and the configuration view and the operation view are extracted and established, respectively, from RAMI4.0 to conceptually describe these two aspects;
- Guided by the configuration and operation views, a turnkey project platform is established in the Advanced Manufacturing Technology Center (AMTC), and the design, development, and application of key enabling tools for the configuration and operation of I4TP are introduced in detail through this platform case;

- The key function process of configuration and operation of the turnkey project platform is verified through product cases, which shows the feasibility of the platform and the good application prospects of the I4TP.

The rest of this paper is arranged as follows. Section 2 reviews the current research status of the two key issues of configuration and operation in I4TP. Section 3 briefly introduces the concept of I4TP, and proposes the configuration view and the operation view. Section 4 details the design and development of key enabling tools for the configuration and operation of the turnkey project platform in AMTC. Section 5 verifies the turnkey project platform through the configuration and operation cases of three product-oriented manufacturing systems. Section 6 summarizes the full text.

2. Related Work

The two key issues involved in I4TP are the rapid configuration and digital operation management of manufacturing systems. This section will briefly introduce the related works in these two aspects.

- Manufacturing system configuration

With the rise of concepts such as flexible manufacturing systems (FMSs) and reconfigurable manufacturing systems (RMSs), the research on the configuration of manufacturing systems has gradually become a hotspot. Especially RMSs, with their core features such as modularity, integrability, customization, convertibility, and scalability [12,13], make the configuration of manufacturing systems one of the key issues in the application of RMSs. In the I4TP, the RMS is also the best paradigm for its turnkey manufacturing system solution at present, which can support the manufacturing system to quickly adapt to production needs [14]. The factors involved in the configuration of the manufacturing system mainly include product modules, manufacturing processes, processing equipment, equipment layout, buffer allocation, etc. [15–18] Sabioni et al. [19] proposed a 0–1 nonlinear integer programming model for mass customization to, in parallel, optimize the configuration of modular products, processing equipment, and equipment layouts, and, based on the Genetic Algorithm (GA), to solve it. Under the social manufacturing environment, Zhang et al. [20] proposed a flexible configuration method for distributed Manufacturing Resources (MRs) based on the Non-dominated Sorting Genetic Algorithm-III (NSGA-III) algorithm and Louvain algorithm. This method can complete high-quality service composition and manufacturing communities' allocation of complex manufacturing tasks under multiple objectives, such as time, cost, and quality, and enable dynamic reconfiguration of MRs under abnormal disturbances. Khettabi et al. [21] established an environment-oriented multi-objective RMS design method, using Nonlinear Multi-objective Integer Programming (NL-MOIP) and four improved evolutionary algorithms to complete the selection of reconfigurable machines and tools. Liu et al. [22] further provided a quad-play CMCO (i.e., Configuration design-Motion planning-Control development-Optimization decoupling) design architecture based on the Digital Twin (DT). A prototype system of the DT manufacturing system design platform is developed and used for the design of flow-type smart manufacturing systems to promote customization of intelligent manufacturing in dimensions such as manufacturing equipment, operation, control, and execution.

- Manufacturing system operation

For the operation management of the manufacturing system, it is first necessary to realize the digitalization and informatization integration of the manufacturing system through technologies such as the Industrial Internet of Things (IIoT) and DT. Further, the real-time monitoring, Predictive Maintenance (PdM), and other health management functions of the manufacturing system are realized by developing data-driven models, and even the deep collaboration and integration of the virtual model and the real system are realized in order to carry out the virtual debugging of newly established manufacturing system [23–25]. Wang et al. [26] proposed a DT-based Big Data Virtual-real Fusion (DT-BDVRL) reference framework for intelligent manufacturing supported by the Industrial

Internet. The method and process for building a Big Data Learning and Analysis (BDLA) model are introduced, and the digital thread in DT-BDVRL's virtual and real fusion analysis, iteration, and closed-loop feedback in the product life cycle process is described. To ensure the reliable operation of machine tools, Luo et al. [27] studied a hybrid method based on the DT model and DT data-driven for PdM and conducted a case study on tool life prediction. Liu et al. [28] proposed a new DT-enabled collaborative data management framework for metal Additive Manufacturing (AM) systems to monitor and analyze the entire production process and presented a typical application scenario for defect analysis of metal AM layers with cloud computing and deep learning. With the continuous deepening and expansion of research on IIoT and DT technologies, the operation management of manufacturing systems can be increasingly supported by digitalization and intelligence.

From the above introduction, it can be identified that the following gaps between the existing related works and the I4TP:

The above research solves the theoretical and technical problems such as the manufacturing system configuration algorithm in a limited range, the data-driven production system design method, and the virtual-real collaboration and integration of the manufacturing system and its components. However, there is still a lack of discussion on I4TP. Compared with the existing research on the multi-factor configuration of manufacturing systems and data-driven manufacturing system operation management, the I4TP emphasizes the rapid acquisition of manufacturing system configuration and operation solutions and provides manufacturers with turnkey services for new product-oriented manufacturing systems. Although there have been some achievements for reference on the basic supporting technologies involved, there is still a lack of theoretical and technical guidance for the development of key functional processes of turnkey projects and reference cases for key enabling tools.

This paper aims to fill these gaps, provides key views of the configuration and operation of I4TP, and provides a design and development case of a turnkey project platform to provide theoretical and technical references for the construction and implementation of turnkey projects.

3. Industry 4.0-Oriented Turnkey Project and Its Configuration View and Operation View

3.1. Introduction of the Industry 4.0-Oriented Turnkey Project

While the concepts of Industry 4.0 and turnkey projects have long been around, they are usually discussed separately. For the I4TP, it is necessary to be located under the Industry 4.0 paradigm. At present, turnkey projects usually refer to projects that meet the needs of a single customer, including the delivery of a complete system [29,30], and there is no clear and unified definition. The I4TP considered in this paper sees providing manufacturing enterprises with turnkey services of manufacturing systems as the main goal, quickly building a product-oriented manufacturing system and running it stably, and efficiently completing the production of new products, including personalized products. Therefore, the definition of I4TP is proposed here: in the context of Industry 4.0, a project that a turnkey service provider uses ICTs and other technologies to quickly form manufacturing systems that satisfy the production needs of customers (manufacturing companies mainly) and implement it into manufacturing verification in order to provide customers with turnkey solutions of manufacturing systems.

As shown in Figure 1, the basic process of generating a turnkey solution is set-up, commissioning, and operation [4,31]. The customer (manufacturer) proposes the product to be processed. After being handled by the feature extractor, turnkey configurator, and turnkey builder, a new manufacturing system comes out and is put into operation under turnkey management. The prerequisite for achieving the rapid formation of the manufacturing system implementation scheme is to have a standardized business process, good synergy among stakeholders and functional modules, and bountiful functional modules that enable efficient automatic and intelligent operation. As for realizing the rapid establishment or reconstruction of the manufacturing system, it is obligatory to integrate and package all kinds of software and hardware in standard modularization and connect each other with a unified interface and data format to fulfill plug-and-play. In addition, with the degradation of production equipment performance, changes in market demands, and innovation of technologies, manufacturing companies need to develop or bring in new equipment and applications, so turnkey projects are also required to have good compatibility and scalability. Therefore, the I4TP should meet the following items:

- Standardized turnkey service business process;
- Good coordination ability;
- Rapid information exchange capability;
- A mass of functional modules for automatic and intelligent operation;
- Standard modular functional components;
- Strong compatibility and scalability.

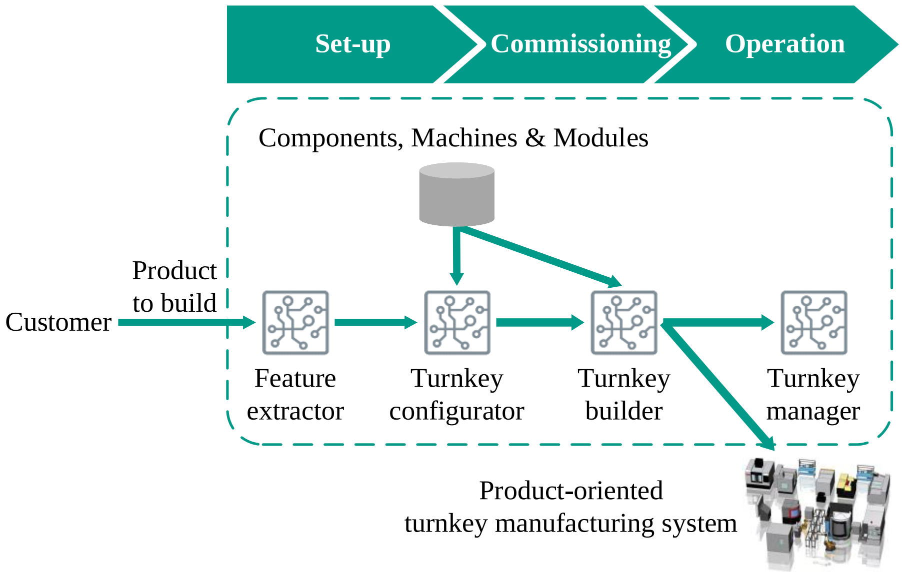

Figure 1. The basic process for generating a turnkey solution [4,31].

Thus, it can be determined that the construction goal of the I4TP is based on the existing manufacturing equipment from different suppliers and through standardized and normalized verification, to make full use of ICTs and the potential for the collaborative process from the web-based approach to carry out the needful parallelization, integration, and automated and intelligent upgrade of the existing manufacturing system development processes, and realize the information interaction with the assets, then under the various constraints, such as cost, quality, delivery time, and operation objectives, quickly establish and form manufacturing systems that adapt to the product needs of the market, and implement it into production verification, providing manufacturing companies with turnkey solutions.

Compared with the existing manufacturing system development process, the biggest feature of the turnkey project is to make full use of ICTs to transform the development process into the configuration process, and to realize the intelligent management of the manufacturing system. Therefore, under the paradigm of Industry 4.0, rapid configuration and intelligent operation of manufacturing systems are two key elements in turnkey projects. To facilitate the participation of all stakeholders involved in the turnkey service, the cloud-based turnkey engineering platform will be the core of the turnkey project. It enables the turnkey project to configure an optimized manufacturing system for a given product and to realize automatic debugging through the plug-and-play scheme. At the same time, the unified standard of the interoperability scheme is met to realize the cooperation between different platform architectures.

3.2. Configuration View and Operation View of the Turnkey Project

A turnkey project is a systematic project involving rich content, such as business, assets, information, and functions. Therefore, a systematic theoretical framework should be used as a guide, especially concerning the construction method of the two key contents of the manufacturing system's rapid configuration and intelligent operation in the I4TP.

The basic purpose of Industry 4.0 is to promote cooperation and collaboration between technical objects, while RAMI4.0 is a structured description of the basic ideas of Industry 4.0, creating digital description rules for technical objects throughout their life cycle and related value changes [5,32–34]. RAMI4.0 is a hierarchical three-dimensional model, including three dimensions: Life cycle & value stream, Hierarchy levels, and Layers. At the same time, an Industry 4.0 Component (I4.0C) reference model, namely the Asset Administration Shell (AAS), is also proposed to provide digital applications corresponding to RAMI4.0 [35–38]. In RAMI4.0 and its derived series of research reports or technical standards and other materials, there are also plug-and-play (or named plug-and-produce) use cases for field devices [39], industry 4.0 asset identification standards [40], Security access control of Industry 4.0 components [41] and other aspects are defined or introduced. In general, RAMI4.0 is committed to the top-down specification and standardization of the information interaction and service application of Industry 4.0 assets, which can provide technical asset frameworks support for various application fields under the Industry 4.0 paradigm. However, RAMI 4.0 has not systematically explored how to construct and apply engineering functional programs, and cannot provide clear guidance for the construction of I4TP, especially the development of functional processes. Therefore, this section proposes a configuration view and an operation view for the two key functional processes of manufacturing system configuration and operation management in turnkey projects, and the concepts and characteristics of these two key functional processes are described.

- Configuration view

The configuration view of the turnkey project is shown in Figure 2. The configuration view covers basic processes such as feature extractor and turnkey configurator. The turnkey project is a project that provides manufacturers with turnkey services for manufacturing systems. The levels it faces are from the manufacturing system to the cooperation between enterprises. In RAMI4.0, it corresponds to the station to the connected world. Of course, the configuration of the system still needs to be based on products, equipment, etc. Through the configuration process, what is obtained is the configuration scheme of the manufacturing system, that is, the prototype of the manufacturing system, so it corresponds to the "Type" stage of the Life Cycle & Value Stream in RAMI4.0. The stakeholders involved in the configuration of the manufacturing system include manufacturers, platform operators, equipment/component suppliers, etc. As the service object of the turnkey project, the manufacturer can designate equipment/component suppliers, etc. It is up to the manufacturer to request a turnkey manufacturing system and to provide data about the product which is to be produced. Production equipment and turnkey platform-compliant equipment data are provided by equipment/component suppliers and stored in or accessible through the equipment database. As the operator of the turnkey project, the platform operator provides core configuration services. Through the mutual matching relationship between products, processes, and equipment, under the constraints or configuration goals of feasibility, security, and economy, and comprehensive considering the layout, scheduling, simulation, and other aspects, a manufacturing system configuration scheme that meets the manufacturer's needs is given. It is worth mentioning that the same enterprise can play different roles in the configuration process at the same time. For example, the manufacturer itself can also act as an equipment/component supplier to provide its existing equipment for the configuration of the manufacturing system.

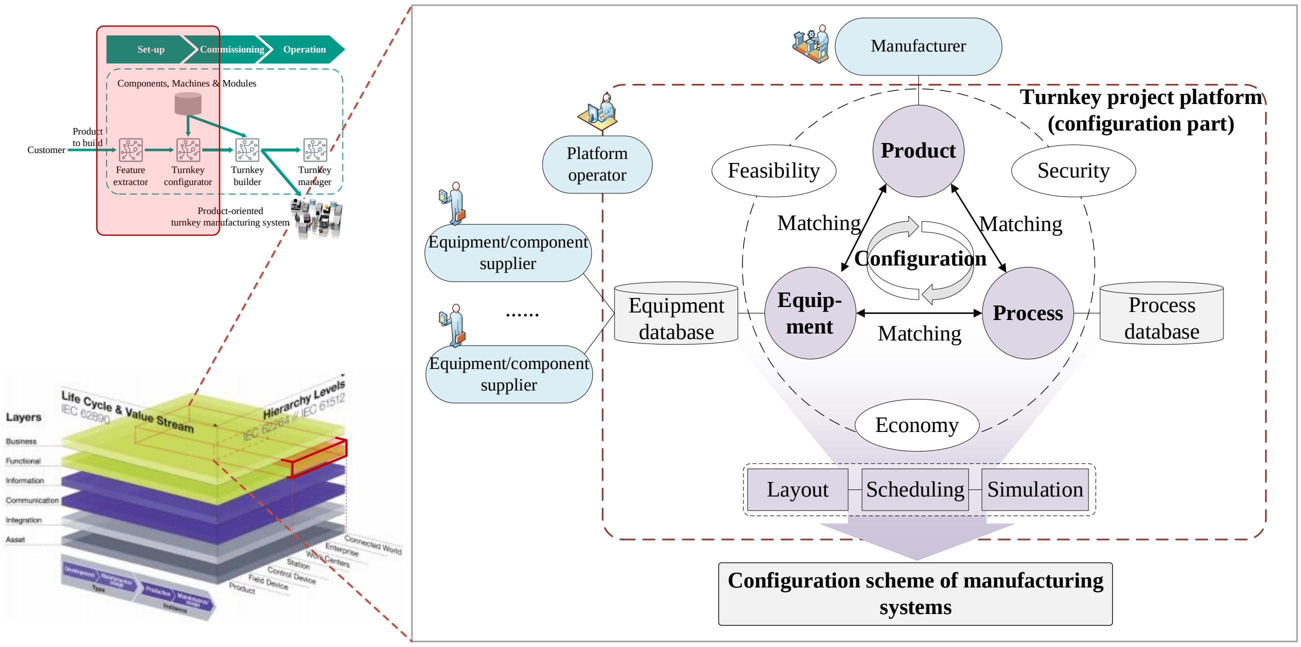

Figure 2. Configuration view.

The entire configuration process is described in detail in the form of a mathematical model. First, it is necessary to extract the processing features based on the information $\boldsymbol{p}$ of the product to be processed by using a feature recognition algorithm or tool (denoted as q). The processing features, optional processes, and optional equipment of the product are represented by $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$, respectively, where

$$\boldsymbol{x} = q(\boldsymbol{p}) \tag{1}$$

In the configuration function of the turnkey project platform, the applicable processing feature range, process database, and equipment database are represented by $\boldsymbol{X}$, $\boldsymbol{Y}$, and $\boldsymbol{Z}$, respectively. Then, the set of possible device configuration schemes can be expressed as

$$\boldsymbol{F} = \{f(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) | \boldsymbol{\alpha}_x \subseteq \boldsymbol{\alpha}_y, \boldsymbol{\beta}_y \subseteq \boldsymbol{\beta}_z, \gamma_x \subseteq \gamma_z, \boldsymbol{x} \subseteq \boldsymbol{X}, \boldsymbol{y} \subseteq \boldsymbol{Y}, \boldsymbol{z} \subseteq \boldsymbol{Z}\} \tag{2}$$

where $f(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ is the matching algorithm model. $\boldsymbol{\alpha}_i$, $\boldsymbol{\beta}_i$, and γ_i all represent a specific attribute set in the set $\boldsymbol{i}$. After further constraints and optimization of feasibility, security, and economy (represented by A, B, C, respectively), the near-optimal equipment configuration scheme $\boldsymbol{F}^*$ can be screened out.

$$\boldsymbol{F}^* = \boldsymbol{k}^* \in \boldsymbol{F} | A(\boldsymbol{k}^*) = 1, B(\boldsymbol{k}^*) = 1, C(\boldsymbol{k}^*) = \min(C(\boldsymbol{k}) | \boldsymbol{k} \in \boldsymbol{F}) \tag{3}$$

According to the equipment configuration scheme $\boldsymbol{F}^*$ and workshop environment $\boldsymbol{I}$, through the layout design method or generation algorithm (denoted as g), the set of optional layout schemes $\boldsymbol{L}$ is obtained. Then, through the process of simulation or mathematical model calculation (denoted as h), the corresponding scheduling scheme set $\boldsymbol{S}$ is obtained. The final manufacturing system configuration scheme $\boldsymbol{R}$ can be obtained by selecting the best combination $(\boldsymbol{L}^*, \boldsymbol{S}^*)$ from $\boldsymbol{L}$ and $\boldsymbol{S}$ according to specific objectives. The configuration scheme $\boldsymbol{R}$ is the unique near-optimal solution given by the whole configuration process model for customer (manufacturer) needs, including equipment configuration, workshop layout, system scheduling, and other aspects.

$$\boldsymbol{L} = \{g(\boldsymbol{F}^*, \boldsymbol{I})\} \tag{4}$$

$$\boldsymbol{S} = \{h(\boldsymbol{F}^*, \boldsymbol{l}) | \boldsymbol{l} \in \boldsymbol{L}\} \tag{5}$$

$$\boldsymbol{R} = (\boldsymbol{F}^*, \boldsymbol{L}^*, \boldsymbol{S}^*) \tag{6}$$

Of course, due to the close interaction among equipment configuration, workshop layout, and production scheduling, the above algorithm models can be further integrated to form multiple collaborative optimization models to improve overall configuration performance.

$$\boldsymbol{R} = J(q, f, A, B, C, g, h) \tag{7}$$

Through the above analysis, the key development process of manufacturing system configuration, a turnkey service-enabling tool, is shown in Figure 3. After developing standardized modular databases that provide basic support, developing algorithm models for key functions, integrating functions, and packaging software and hardware, a manufacturing system configuration enabling tool is ultimately formed.

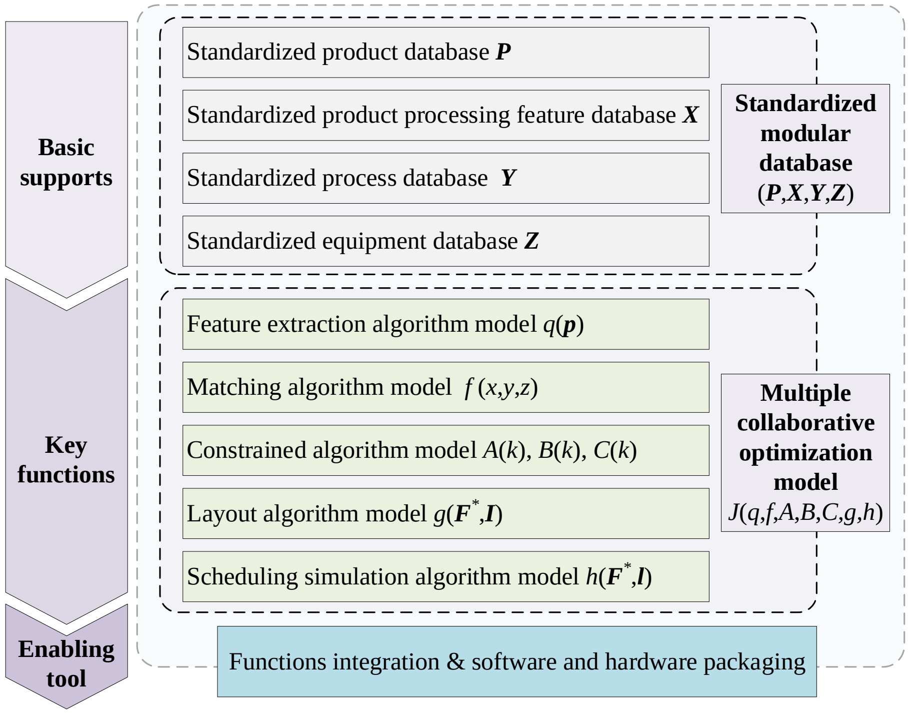

Figure 3. The key development process of the manufacturing system configuration service-enabling tool.

- Operation view

The operation view of the turnkey project is shown in Figure 4. The operation view of the turnkey project involves the construction and management of the manufacturing system, which, similarly to the configuration view, corresponds to the hierarchy level range from station to connected word in RAMI 4.0. In the turnkey project, the operation process of the manufacturing system is the instantiation of the configuration result and the intelligent management after instantiation, so it belongs to the "Instance" stage of the Life Cycle & Value Stream. The stakeholders involved in the operation of the manufacturing system mainly include manufacturers, platform operators, equipment/component suppliers, material/parts suppliers, and IoT suppliers. Similarly, manufacturers can select suppliers. The production equipment is provided by equipment/component suppliers, and the production equipment is integrated into the workshop in a standard modular form as much as possible and has advanced functions such as plug-and-play and automatic debugging, to ensure the rapid construction of the manufacturing system. Raw materials for producing products are provided by material/parts suppliers. IoT suppliers provide equipment interconnection services to achieve reliability data acquisition in the workshop. The platform operator obtains real-time data on physical assets from the IIoT platform connected to the equipment and integrates it. According to the hierarchical relationship of the "component-equipment-manufacturing system", real-time monitoring, fault diagnosis, Remaining Useful Life (RUL) prediction, PdM, and other various operation and maintenance functions are realized layer by layer. These functions are integrated upward, and the intelligent operation and health management of the entire manufacturing system are finally realized. Once the whole system has been confirmed to be operating normally and smoothly, the complete turnkey solution can be delivered to the manufacturer. When manufacturers have new production requirements, the manufacturing system can be reconfigured, and the functional structures in the IIoT platform and turnkey project platform are also updated.

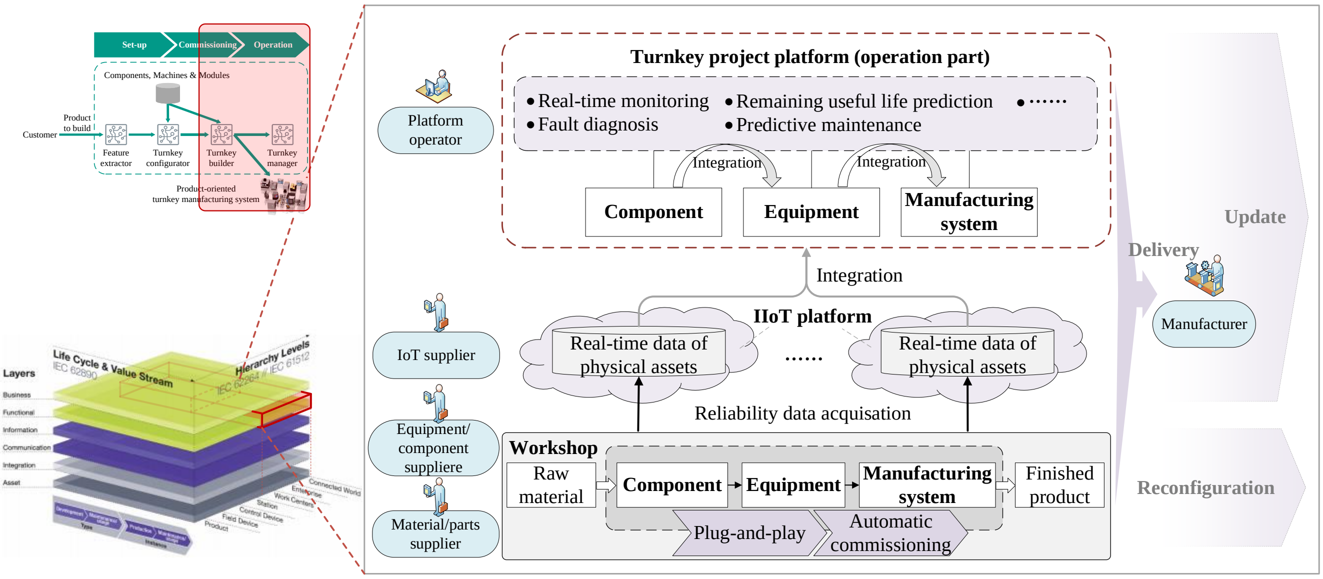

Figure 4. Operation view.

To facilitate analysis and discussion, a mathematical description of the operation process is further established. First, we integrate the real-time data obtained by using the IIoT platform to facilitate the realization of subsequent operation and health management functions.

$$\boldsymbol{D}_O = \boldsymbol{D}_{P1} \oplus \boldsymbol{D}_{P2} \oplus \cdots \oplus \boldsymbol{D}_{Pm} \tag{8}$$

where $\boldsymbol{D}_{Pi}$ represents the collection of real-time data from the supplier i. Using these real-time data, the functional set of each level of the "component-equipment-manufacturing system" can be implemented and integrated layer by layer according to the configuration scheme $\boldsymbol{R}$ of the manufacturing system. The operation and health management function sets of parts, equipment, and manufacturing systems are, respectively, denoted as $\boldsymbol{M}_F$, $\boldsymbol{M}_D$, $\boldsymbol{M}_S$, and the functional models of which are, respectively, denoted as u_i, v_i, w_i, and the function sets at each level of "component-equipment-manufacturing system" can be expressed as

$$\boldsymbol{M}_F = \{u_1(\boldsymbol{D}_{F1}|\boldsymbol{D}_{F1} \subseteq \boldsymbol{D}_O), \cdots, u_n(\boldsymbol{D}_{Fn}|\boldsymbol{D}_{Fn} \subseteq \boldsymbol{D}_O)|\boldsymbol{R}\} \tag{9}$$

$$\boldsymbol{M}_D = \{v_1(\boldsymbol{M}_{F1}, \boldsymbol{D}_{D1}|\boldsymbol{M}_{F1} \subseteq \boldsymbol{M}_F, \boldsymbol{D}_{D1} \subseteq \boldsymbol{D}_O), \cdots, v_r(\boldsymbol{M}_{Fr}, \boldsymbol{D}_{Dr}|\boldsymbol{M}_{Fr} \subseteq \boldsymbol{M}_F, \boldsymbol{D}_{Dr} \subseteq \boldsymbol{D}_O)|\boldsymbol{R}\} \tag{10}$$

$$\boldsymbol{M}_S = \{w_1(\boldsymbol{M}_{D1}, \boldsymbol{D}_{S1}|\boldsymbol{M}_{D1} \subseteq \boldsymbol{M}_D, \boldsymbol{D}_{S1} \subseteq \boldsymbol{D}_O), \cdots, w_t(\boldsymbol{M}_{Dr}, \boldsymbol{D}_{Sr}|\boldsymbol{M}_{Dr} \subseteq \boldsymbol{M}_D, \boldsymbol{D}_{Sr} \subseteq \boldsymbol{D}_O)|\boldsymbol{R}\} \tag{11}$$

Among them, $\boldsymbol{D}_{Fi}$, $\boldsymbol{D}_{Di}$, and $\boldsymbol{D}_{Si}$ represents the data subset of $\boldsymbol{D}_O$ related to the functional model u_i, v_i, and w_i. $\boldsymbol{M}_{Fi}$ represents a set of the operation and health management function set of a device's components that are related to the functional model v_i of the device level, and is integrated through the model v_i. $\boldsymbol{M}_{Di}$ represents a set of the operation and health management function of a manufacturing system's devices that are related to the functional model w_i of the manufacturing system level, and is integrated through the model w_i.

Once the manufacturing system is operational, the turnkey solution $\boldsymbol{TKS} = (\boldsymbol{R}, \boldsymbol{M}_F, \boldsymbol{M}_D, \boldsymbol{M}_S)$, i.e., the near-optimal set of configuration and operation solutions can be delivered to the manufacturer. When a manufacturer needs to produce a new product, they can realize the conversion of the turnkey solution according to a certain reconstruction and update method (denoted as T) based on the existing turnkey solution.

$$\boldsymbol{TKS}' = (\boldsymbol{R}', \boldsymbol{M}'_F, \boldsymbol{M}'_D, \boldsymbol{M}'_S) = T(\boldsymbol{R}, \boldsymbol{M}_F, \boldsymbol{M}_D, \boldsymbol{M}_S) \tag{12}$$

The key development process of the service-enabling tool for manufacturing system operation is shown in Figure 5. Based on the reliability data acquisition of components, equipment, and manufacturing systems and the standardized real-time database formed by integration, develop various levels of operation and health management models and reconfiguration and update algorithm models. Finally, we integrate these basic supports and various key functions and packaged them on software and hardware to form a manufacturing system operation service-enabling tool.

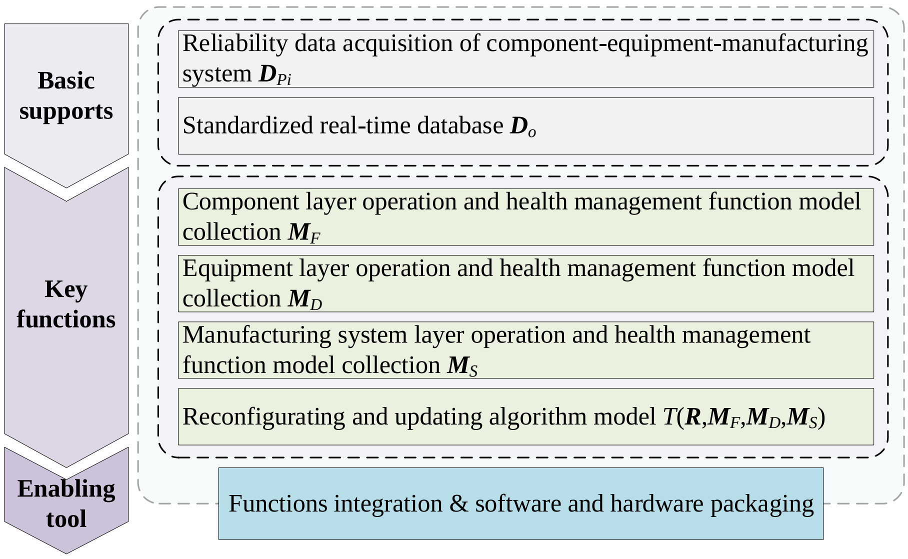

Figure 5. The key development process of manufacturing system operation service-enabling tool.

4. Design and Development of Key Enabling Tools for Manufacturing System Configuration and Operation: Taking AMTC as an Example

Under the configuration view and the operation view, different specific construction plans will be formed according to different manufacturing industries and different actual needs. Here, the mapping between key views of the turnkey project and specific applications is shown by taking the development of AMTC's turnkey project platform as an example.

4.1. Development Background of the Turnkey Project Platform in AMTC

To create an environment for the research, demonstration, and teaching of intelligent manufacturing-related technologies, and to provide technical services for related enterprises, AMTC needs to build turnkey projects to meet the processing needs of diversified products. As a research base and demonstration center of advanced manufacturing technology, AMTC has abundant equipment and technical resources to support the construction of turnkey projects.

- Equipment supports

As the basic support for the turnkey project, the main equipment in the AMTC workshop currently is shown in Figure 6. The left part is mainly large and medium-sized equipment assets. These assets can meet the needs of turnkey projects through network transformation and integration and packaging. These devices are not easy to move, so the layout usually remains unchanged during actual processing, but configuration and reconfiguration can still be achieved in terms of scheduling. The right part is a modular production unit based on the i5Blocks intelligent manufacturing demonstration line, it can be automatically combined to form a new production line according to the configuration results, and has the advantage of quick replacement, which will give full play to the advantages of turnkey projects. In addition, when serving manufacturers, i.e., configuring and building manufacturing systems, the optional assets from the corresponding manufacturers and suppliers will also be included in the asset category of the turnkey project.

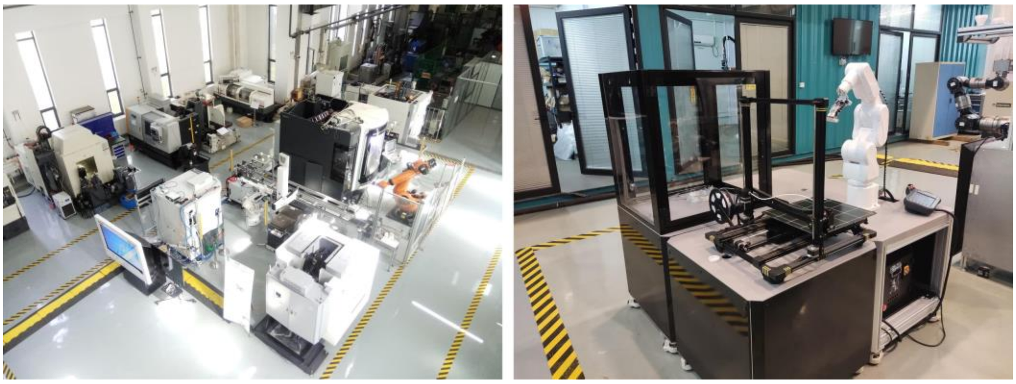

Figure 6. Devices in the AMTC workshop.

- Machine communication supports

In terms of machine communication, the communication from the physical layer to the information layer is composed of three solutions, as shown in Figure 7, provided by iSESOL, Microcyber, and HUAWEI, respectively. Among them, the solution provided by iSESOL uses the iPORT protocol to communicate between devices and the cloud. It has a strong compatibility with various common industrial communication protocols. The main machine tools in the AMTC workshop are connected to collect internal data through this solution, including the DMU65 machining center, the M1.4 Machining center, etc., and a vibration sensor is installed on the spindle of the M1.4 machining center to collect its vibration data. Microcyber is more focused on the security of the workshop's local area network and adopts the data security encryption technology based on the multi-key distribution mechanism and Modbus security communication technology based on the national cryptographic algorithm and security protocol, etc. Microcyber provides vibration and temperature sensors, machine tool access points, and other equipment, which can be used for data acquisition inside and outside the machine tool and workshop environment data. Currently, this solution is mainly used for equipment vibration and temperature data acquisition in the AMTC workshop. The solution provided by HUWEI focuses on the industrial application of 5G technology, supports the most commonly used top 7 industrial communication protocols, and establishes application scenarios on the TS2 conveyor in the AMTC workshop for material transfer locations monitoring. In addition, the iSESOL cloud also provides the OpenAPI open service interface, which can be interconnected with other industrial cloud platforms or functional applications to jointly complete real-time monitoring and digital management of the entire workshop.

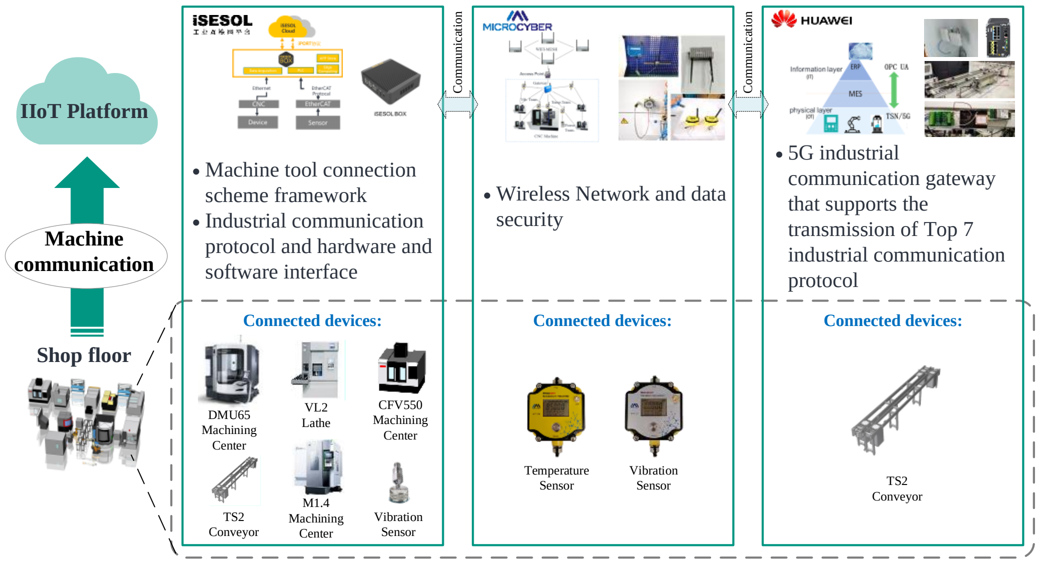

Figure 7. Machine communication solutions.

4.2. The Overall Functional Design of the Turnkey Project Platform

Based on the aforementioned analysis and the basic environment of AMTC, this section combines DT technology, artificial intelligence technology, and actual needs to design the overall function of the turnkey project platform. The functional structure of the obtained turnkey project platform is shown in Figure 8. It is mainly composed of two sub-platforms: the system configuration platform and the operation management platform. The two sub-platforms correspond to the two key functional processes of the manufacturing system configuration and operation management of the turnkey project, that is, the enabling tools for these two key functional processes. The turnkey project platform is mainly oriented to the production of designed products and takes information, such as product models, materials, drawings, and production indicators, as input. Then, the steps of processing feature extraction, manufacturing process matching, system configuration, workshop layout generation, scheduling simulation and optimization are completed in the system configuration platform. The configuration results are handed over to the workshop staff to complete the system construction or reconstruction. The operation management platform realizes real-time production monitoring, analyzes the operation status of equipment/components, and formulates PdM strategies by collecting real-time operation data of workshop equipment/components.

4.3. Design and Development of the System Configuration Platform

The detailed functional structure design of the system configuration platform is shown in Figure 9. MongoDB is used as the database for storing various data involved in the manufacturing system configuration process. First, the platform user imports the information of the product to be processed, and after the import is completed, a feature extraction instruction is issued to the backend server. The server identifies the product features and the relationship between the features based on the STEP file of the product and outputs a list of processing features. Then, the process matching instruction is issued, and the server performs the identification and modeling of the interdependence between the parameters of the product, processing features, etc. At the same time, it analyzes its impact and risk and performs process matching based on the interdependence between the processing features and the process, and the corresponding process list is outputted. Next, the user sets various requirements for product production within the allowable range of the platform, including configuration optimization goals such as the lowest production cost and highest production efficiency. After that, the user issues system configuration instructions, and the server according to equipment, tools, and other configuration resources and product requirements, configures the manufacturing system based on GA and outputs the configuration result. Finally, the user issues a workshop layout generation instruction, and the server generates the workshop layout scheme based on GA, according to the configuration result and equipment information. Plant Simulation is used to carry out scheduling simulation and optimization of the layout scheme to output the final workshop layout and scheduling scheme.

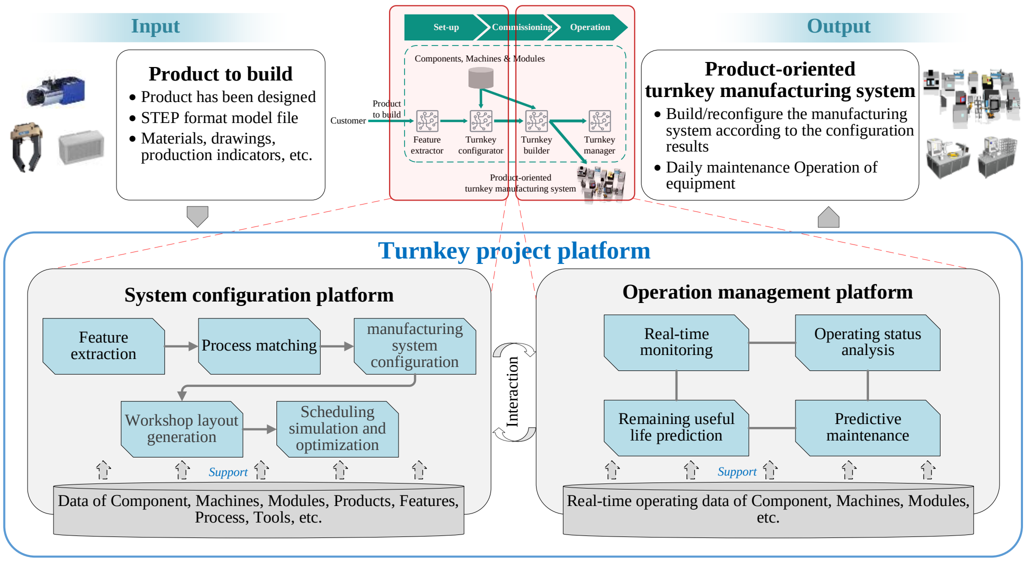

Figure 8. The functional structure of the turnkey project platform.

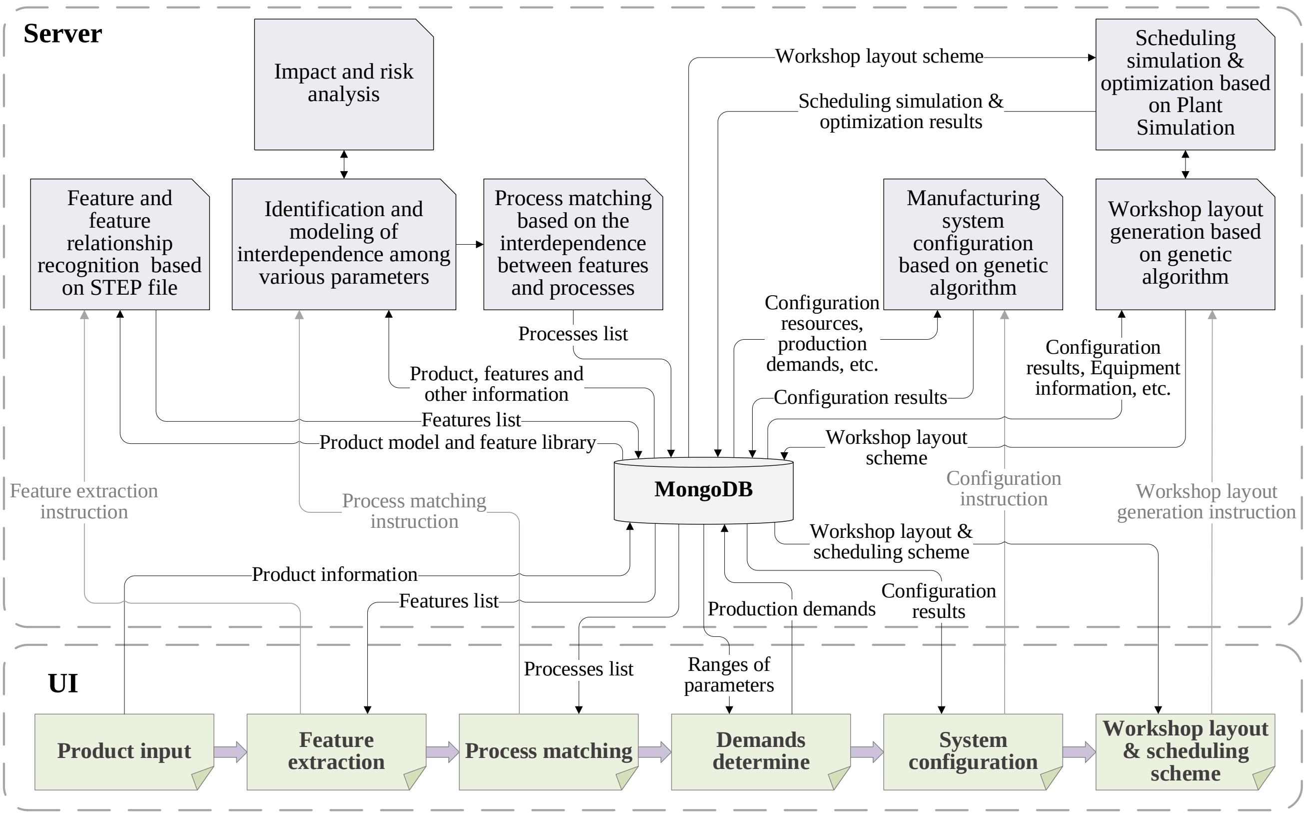

Figure 9. The detailed functional structure design of the system configuration platform.

The User Interface (UI) of the system configuration platform developed according to the design scheme is shown in Figure 10. Considering the convenience of the application, the development method adopted is a web-based method, which belongs to a website application project and is a Browser/Server (B/S) application structure. Apache is used to host web services and the XAMPP package is applied for the configuration management of Apache. The main structure of the backend server is developed with Python3, and the frontend browser pages are written with Hyper Text Mark-up Language 5 (HTML5), Cascading Style Sheets (CSS), and JavaScript.

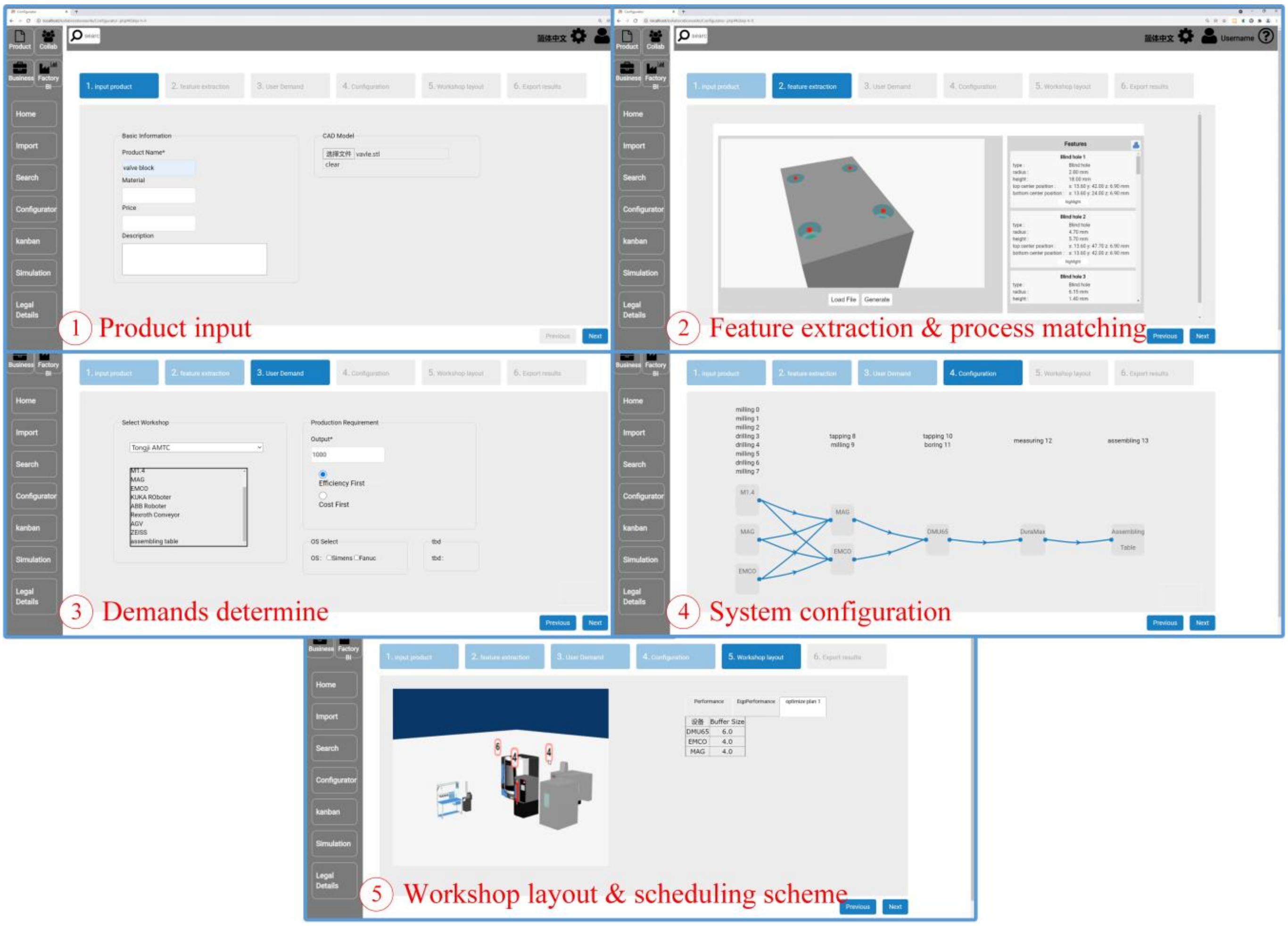

Figure 10. The UI of the system configuration platform.

During the entire system configuration process, the system configuration platform integrates feature extraction, process matching, equipment configuration, layout generation, scheduling simulation and optimization into the backend server. Platform users can quickly obtain manufacturing system configuration schemes with simple operations instead of tedious and time-consuming manufacturing system design processes. What's more, manufacturers who need to build new manufacturing systems can use the services provided by this platform to obtain solutions that meet their needs without extensive expertise in manufacturing system design.

4.4. Design and Development of the Operation Management Platform

The detailed functional structure design of the operation management platform is shown in Figure 11, and the concept of AAS [5,33,35,37] is introduced for description. In the operation management platform, according to the structural level of the manufacturing system, several machine communication solutions introduced in Figure 7 are used to realize the information interaction between the key components-equipment-system and the server in the workshop. Corresponding to the different levels of components-equipment-system in the server, a management module (i.e., AAS) is constructed to manage each key asset at each level. Compared with the current common way of independent monitoring of key equipment/components, the hierarchical operation management scheme is more conducive to the assessment and prediction of production status from the perspective of the overall manufacturing system in the production process. Thereby, the operation and maintenance decisions can be made or adjusted promptly. Combined with the actual needs of AMTC workshops, different management strategies are adopted for different assets. Taking the DMU65 machining center as an example, the RUL prediction of the bearings in its spindle and feeding system is based on the Support Vector Machine (SVM). The spindle and feeding system use different methods to realize fault diagnosis and PdM functions based on the RUL prediction results of the bearings. On this basis, data from other sources in the DMU65 machining center is also integrated to realize real-time monitoring, fault diagnosis, and PdM of the entire machine at the equipment level. Management measures such as real-time monitoring are also implemented for other equipment, such as robots and conveyors. By integrating the data of the underlying equipment with the results of fault diagnosis, PdM, and other functions, the real-time monitoring, fault diagnosis, and PdM of the manufacturing system can be further realized. The real-time operation data of assets at all levels and the analysis results of various health management functions are stored in the database and displayed to users in real time. Users can intuitively view the operating status of the manufacturing system and its equipment and components through the UI, and conduct inspection, maintenance, repair, replacement, etc. based on the analysis results of various health management functions. When the manufacturing system needs to be reconstructed, the communication relationship between the AASs in the server will also be updated synchronously.

Combining the characteristics and advantages of the three machine communication solutions in Figure 7, as well as their currently connected device assets, the developed operation management platform is shown in Figure 12, consisting of four parts. The first part adopts the machine communication solution provided by iSESOL, which connects the main equipment in the workshop and uploads the data to the cloud for real-time monitoring. The monitored equipment operation data includes spindle speed, spindle load, feed speed, number of processed workpieces, running time, etc. The second part also uses the solution provided by iSESOL to connect equipment, and then develop local functions in the iSESOL BOX, including RUL prediction of the bearing, fault diagnosis of the spindle, feeding system, and machine tool, and PdM of the spindle, feeding system, and machine tool. The third part adopts the solution provided by Microcyber to realize the temperature and vibration monitoring of the machine tool and workshop environment. The fourth part adopts the solution provided by HUAWEI, uses the 5G network to communicate, and monitors the position of the workpiece on the conveyor.

In the operation management platform shown in Figure 12, the web-based UI of the first part is provided by iSESOL directly, and the UIs of the rest parts are also developed in a web-based way. In the first part, the device operation data is collected and uploaded to the cloud, which can be accessed by remote users, providing cloud services. The rest are connected through the local area wireless networks of the workshop, and the local equipment in the workshop is used to provide computing support for various functions, and all provided are edge services. The entire operation management platform adopts a distributed management strategy combining cloud and edge, which can fully guarantee the flexibility of the manufacturing system and facilitate subsequent system reconstruction. Of course, current edge services can also be integrated into the cloud as needed. In addition, in the future, users can obtain these functional applications by downloading Applications (APPs) on mobile clients connected to the cloud.

After completing the construction or reconstruction of the manufacturing system according to the configuration scheme and starting the trial operation, the whole process of digital management of the workshop production is carried out through the operation management platform. It can quickly verify the feasibility and reliability of the new manufacturing system to ensure that it can be put into operation smoothly. Meanwhile, it also provides manufacturers with a complete set of turnkey manufacturing system solutions, including follow-up operation management, so that manufacturers can directly operate the manufacturing system without the need for separate system operation testing and network design transformation.

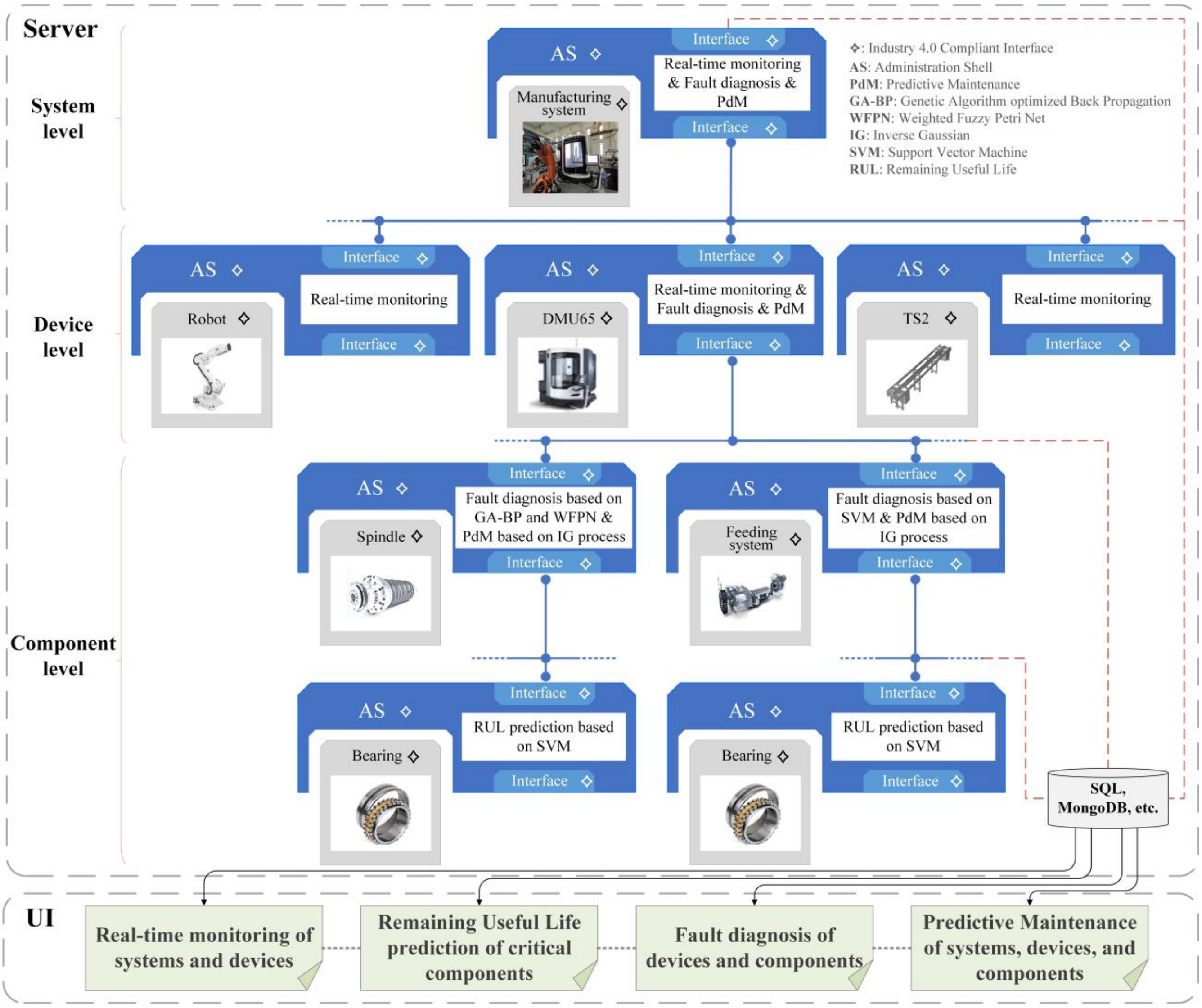

Figure 11. The detailed functional structure design of the operation management platform.

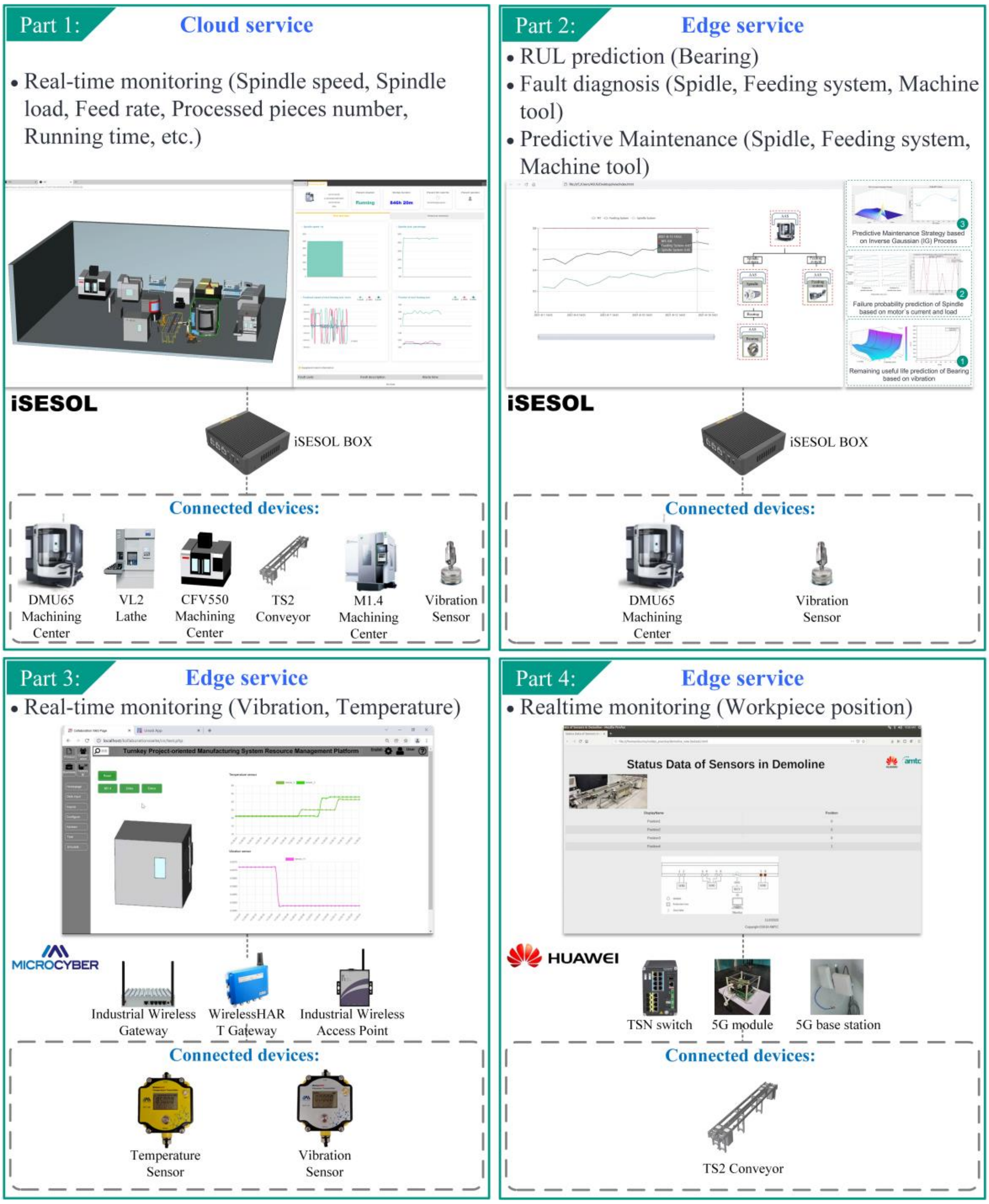

Figure 12. The devices' connection and UIs of the operation management platform.

5. Product-Oriented Manufacturing System Configuration and Operation Cases

To verify the developed turnkey project platform, three products, the hydraulic valve block, the gripper base, and the automotive fuel cell (model), are used as verification cases.

This platform has properly simplified the evaluation of production efficiency and production cost in the configuration process. The efficiency and cost indexes are obtained by weighting the sum of several key parameters, and the efficiency-cost comprehensive index is further constructed by weighting the efficiency and cost indexes. This comprehensive index is used for scheme comparison. The factors considered in the calculation of the production efficiency index include the spindle speed, the feeding speed, the power, the average tool change duration, the tool change times of the equipment, etc. While the factors considered in the calculation of the production cost index include the tool price, the equipment price, the average processing cost of the equipment to complete a single process step, etc. The weight of each parameter is obtained by the analytic hierarchy process. The smaller the efficiency-cost comprehensive index, the better the solution.

- Hydraulic valve block

The manufacturing system configuration and operation verification results of the hydraulic valve block case are shown in Figure 13. The material of the hydraulic valve block is cast iron, and its blank is a casting, which needs to complete the processing of multiple planes, smooth holes, threaded holes, and stepped surfaces. Through the functional process of the system configuration platform, the manufacturing system configuration scheme under two different optimization objectives of production efficiency priority and production cost priority is obtained. Compared with the original manufacturing system scheme, when considering efficiency first, the comprehensive index of the system configuration scheme given by the platform is 0.24, which is much better than the 0.81 of the original system. When considering cost first, the system configuration scheme can also perform better. According to the equipment configuration results and layout generation results, the Plant Simulation software is further used for simulation and optimization. The number next to the equipment model represents the optimized buffer capacity matched with the equipment. The configuration scheme that prioritizes production efficiency is selected for implementation. The operation management part in Figure 13 shows the operation of the new manufacturing system and the operation management platform at a certain time. It can be seen that the turnkey project platform can configure the equipment required for the production of new products and generate a reasonable workshop layout according to different user needs. Optimization results such as buffer capacity are given after simulation and digital management is executed when new manufacturing systems are put into service.

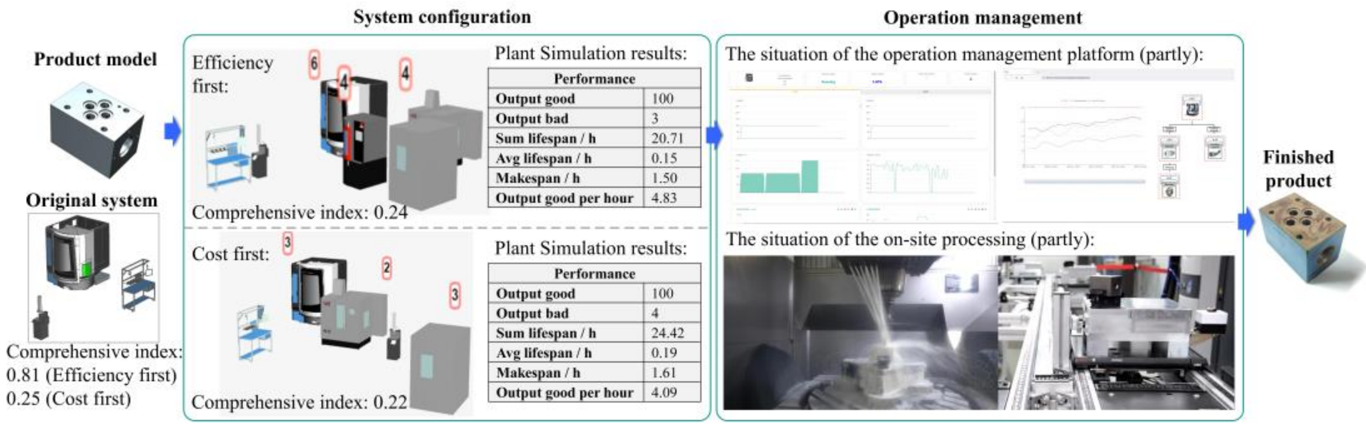

Figure 13. Configuration and operation of the hydraulic valve block manufacturing system.

- Gripper base

The configuration and operation of the manufacturing system for the gripper base case are shown in Figure 14. The material of the gripper base is aluminum alloy, and its blank is an aluminum alloy block. Multiple planes, slots, and holes are some of the features to be machined. The manufacturing system configuration scheme can be quickly obtained by using the system configuration platform. According to the efficiency-cost comprehensive index of different solutions, compared with the original manufacturing system solution, the system configuration platform can provide a better solution in the two optimization directions of efficiency first and cost first. The efficiency-first scheme is adopted for product production, and the operation management platform effectively guarantees the safety and stability of the production process.

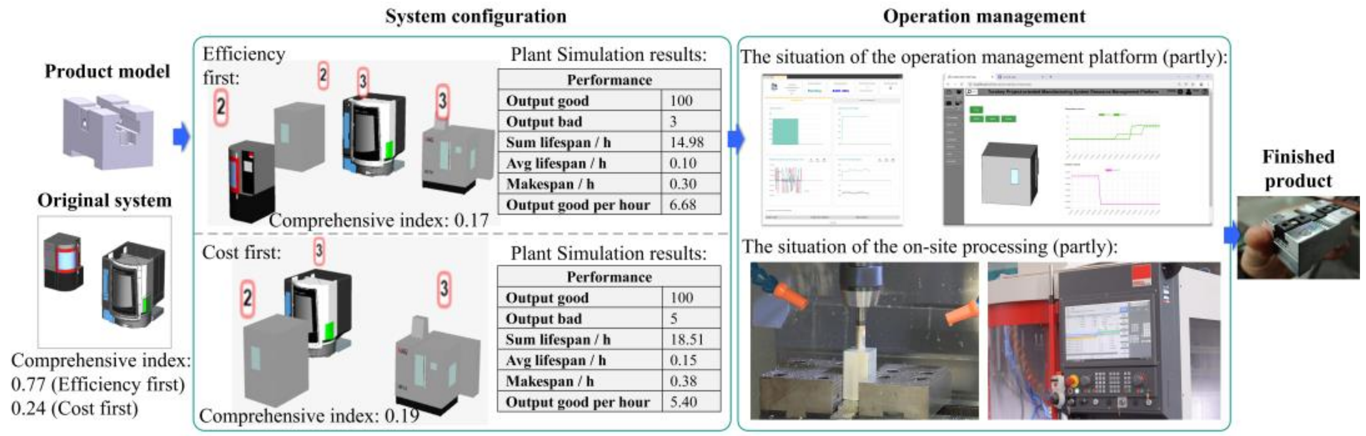

Figure 14. Configuration and operation of the gripper base manufacturing system.

- Automotive fuel cell (model)

The production of automobile fuel cells is divided into two main processes, 3D printing of air intake grilles and assembly of air intake grilles and ready-made battery stacks. To simulate this process in order to verify its feasibility and save costs, the Polylactic Acid (PLA) material is used to replace the original material to establish an imitated production scene. The manufacturing system in this case is built for the first time. The configuration scheme obtained by the system configuration platform and the on-site processing situation are shown in Figure 15, and the equipment used is modular units. The currently used modular units have not been connected to the operation management platform, but the potential of the turnkey project platform can still be reflected through the generation of configuration schemes by the system configuration platform and the on-site processing.

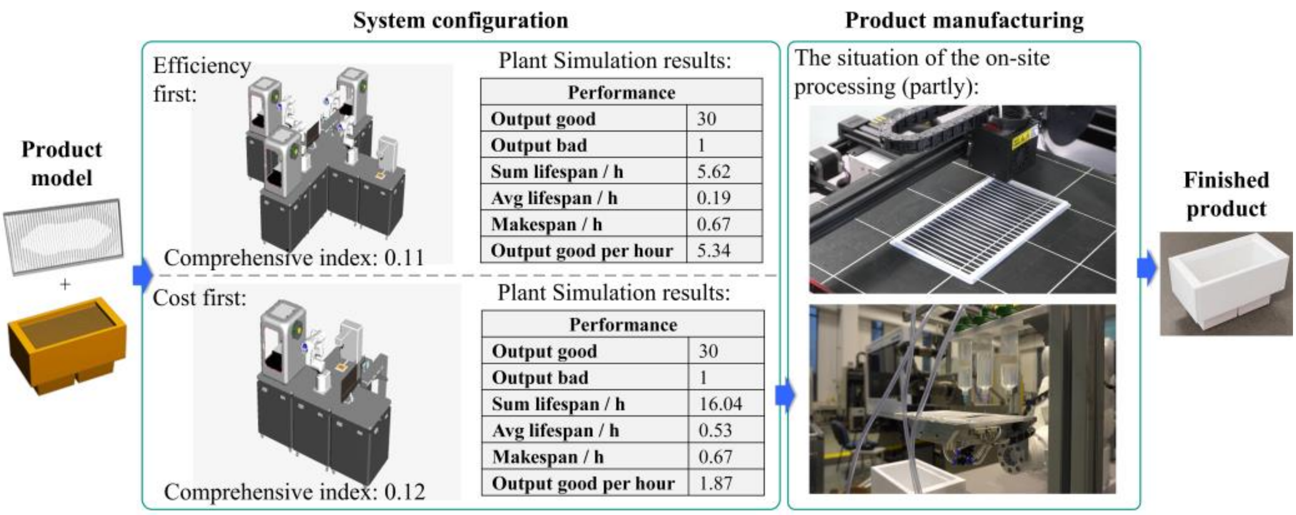

Figure 15. Configuration and field situation of the fuel cell (model) manufacturing system.

To save verification costs, only a small number of finished products have been produced for each product in practice, and all of them meet the product design requirements. This shows that the turnkey solutions for the three products are feasible.

At present, the turnkey project platform has completed the development, integration, and encapsulation of many key functional models under the guidance of the configuration and operation views, forming two key enabling tools, the system configuration platform and the operation management platform. The above three cases further prove the feasibility and effectiveness of the turnkey project platform, as well as the huge application potential of the I4TP. The I4TP makes it possible to rapidly configure and operate the new manufacturing system. Although the above cases are only the application of the turnkey project platform in the same workshop, with the continuous enrichment of built-in functions of the platform, it will be fully able to adapt to emerging manufacturing modes such as social manufacturing. It can provide a platform for various manufacturers, suppliers, and other stakeholders to jointly participate in the task allocation, docking, and communication of the product production.

6. Conclusions and Summary

In response to wider personalization and transforming market demands, manufacturing enterprises need to respond more quickly to realize the rapid establishment and operation of related manufacturing systems. However, numerous enterprises, especially small and micro enterprises, cannot cope with the rapid updating of product-oriented manufacturing system configurations alone. Therefore, it is very necessary to make full use of the existing ICTs to carry out the construction of turnkey projects and provide these enterprises with turnkey services of manufacturing systems. Focusing on the generation process of the turnkey project, this paper proposes a configuration view and an operation view for the two key contents of the system configuration and operation in the turnkey project, to provide a theoretical basis for the development of the key function process of the turnkey project. To a certain extent, it makes up for the defect that the existing reference architecture cannot provide specific guidance for the construction of turnkey projects. At the same time, the turnkey project platform in AMTC is used as a demonstration case to provide a reference for the development and application of key enabling tools for configuration and operation. The research results are summarized as follows:

- According to the basic process of generating the turnkey scheme and the characteristics of the turnkey project, the configuration view and the operation view of the turnkey project are proposed based on RAMI4.0. The configuration and operation processes are described in the form of mathematical models, and the key function development processes of configuration and operation enabling tools are given;
- Guided by the configuration and operation views, relying on AMTC's equipment and machine communication network support, the overall functional design of the turnkey project platform is carried out according to actual needs. The functional structure design and application development of the system configuration platform and the operation management platform are focused on. Various functions of configuration and operation are integrated into the servers, and simple and easy-to-use UIs are provided. This provides users with turnkey services for the rapid configuration of manufacturing systems and intelligent operation management;
- The developed turnkey project platform is verified by taking three products as case studies. The results show that the system configuration and operation management functions of the turnkey project platform can operate normally, and they have achieved good application results, which can meet the rapid configuration and efficient operation management requirements of the manufacturing system.

In general, the developed turnkey project platform has the following advantages. (1) This platform makes it possible to quickly obtain turnkey solutions for manufacturing systems that are difficult to achieve with traditional methods. (2) It can optimize the production efficiency, production cost, and other objectives of the manufacturing system in the rapid configuration process. (3) It can provide a hierarchical health and operation management scheme for the manufacturing system, and compared with the independent monitoring mechanism between equipment/components, it is more conducive to ensuring the secure and stable operation of the manufacturing system.

At present, the turnkey project platform in AMTC provides only research examples. The construction of turnkey projects from functional development to practical application still requires a lot of research work, including rapid product development, processing feature extraction, process matching, manufacturing system configuration, workshop layout generation and optimization, modular production equipment design and implementation, real-time monitoring and intelligent control of production, coordination mechanism between manufacturers and suppliers, etc., all need to be developed, improved and promoted. These factors require further organic integration in the future.

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