A novel intelligent manufacturing mode with human-cyber-physical collaboration and fusion in the non-ferrous metal industry

Qing Liu · Min Liu · Zichun Wang · Feng Yan · Yingyi Ma · Weiming Shen

Received: 25 June 2021 / Accepted: 15 October 2021 / Published online: 4 November 2021
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
The non-ferrous metal industry is one of the most important parts of China’s process industry and has an extremely important strategic position in the national economy. However, there are many problems in the process of non-ferrous metal smelting: (1) The utilization rate of resource and energy is low in the production process. (2) Large amount of waste emissions have caused prominent environmental problems. (3) The added value of non-ferrous metals is low; besides, the product homogenization is serious. To solve these problems, a novel intelligent manufacturing mode with human-cyber-physical (HCP) collaboration and fusion is constructed from three aspects: (1) an intelligent manufacturing system with HCP collaboration and fusion, (2) a service-based ecosystem platform, and (3) a sustainable business model. The proposed manufacturing mode can make the process of non-ferrous smelting safe, efficient, intelligent, and green. A case study on the largest copper smelting enterprise in the world elaborates the digital twin-based manufacturing system collaborative platform architecture, the framework of the service-based ecosystem platform, and the sustainable business model canvas, which are built by the proposed intelligent manufacturing mode. The results of this paper contribute to the research and practice of non-ferrous metals enterprise’s manufacturing mode.

Keywords Non-ferrous metal industry · Intelligent manufacturing mode with human-cyber-physical collaboration and fusion · Service-based ecosystem platform · Sustainable business model · Digital twin

1 Introduction

Non-ferrous metals are basic raw materials for the development of the national economy and are strategic materials for defense and military industries. China’s production and consumption of non-ferrous metals have been top-ranked for 18 years. China is worthy of name a non-ferrous metals power and remains stable rise. As one of the most important parts of China’s process industry, the non-ferrous metal industry develops strongly and is significant to the manufacturing power strategy. Currently, the main process and equipment for non-ferrous metal smelting in China are advanced globally, and a relatively complete modern non-ferrous metal industrial system has been formed [1].

However, China is not yet a power in the non-ferrous metal industry primarily due to these problems: (1) The smelting process of non-ferrous metal is long, and there are correlation and coupling between different processes; moreover, data from different sources, for example, manufacturing domain, product domain, and management domain, are separated. (2) The demands of refined management and control for low cost, high
efficiency, high quality, and safety are urgent, and production, supply, and marketing are disjointed, so the production efficiency, energy consumption, material consumption, and pollutant emission of non-ferrous metal smelting are affected. (3) The types of non-ferrous metal product are stable and its added value is low. These problems are related to the manufacturing system, the production system, and the business model. In order to solve these problems systematically and comprehensively, a novel intelligent manufacturing mode with human-cyber-physical (HCP) collaboration and fusion is constructed from three aspects, (1) an intelligent manufacturing system with HCP collaboration and fusion, (2) a service-based ecosystem platform, (3) a sustainable business model, to make the process of non-ferrous metal smelting safe, efficient, and green.

With the development of the industrial Internet, big data, artificial intelligence (AI), and other new-generation information technologies (NGIT), an intelligent manufacturing mode with HCP collaboration and fusion has become possible. In the current digital economy era, the deep integration and fusion between the non-ferrous metal industry and the NGIT, such as the new-generation AI [2–4], Internet of Things (IOT) [5, 6], cloud computing [7, 8], big data [9, 10], industrial Internet, and digital twin [11], provide a great opportunity for the non-ferrous metal industry to breed a new intelligent manufacturing mode with HCP collaboration and fusion, which can solve the above problems and bring new development opportunities to non-ferrous metals enterprises.

Combined with the development of information technology and the demand change of manufacturing mode, this paper discusses a novel intelligent manufacturing mode with HCP collaboration and fusion for the non-ferrous metal industry in detail. First, Sect. 2 discusses the proposed intelligent manufacturing mode with HCP collaboration and fusion in the non-ferrous metal industry. The manufacturing system, the service-based ecosystem platform, and the business model in non-ferrous metal industry, which accommodated the proposed manufacturing mode, are discussed in Sects. 3, 4, and 5, respectively. Next, a case study is depicted from the largest copper smelting enterprise in the world in Sect. 6, and the intelligent manufacturing mode with HCP collaboration and fusion, manufacturing system architecture, service-based ecosystem platform architecture, and business model innovation (BMI) process are given to build a collaborative intelligent manufacturing platform system.

2 The intelligent manufacturing mode with HCP collaboration and fusion

2.1 Manufacturing mode model

Koren et al. mentioned in “global manufacturing revolution” that “manufacturing mode is a revolutionary integrated production mode in response to changes from social and market demand” [12]. A manufacturing mode represents the form or operation mode of manufacturing enterprises in production, operation, management, organization structure, and technical system.

Manufacturing enterprises must make rapid response to markets from anywhere in the world to maintain their global competitiveness. As shown in Fig. 1, the responses come from three aspects (internal driving force): the product system, the manufacturing system, and the business model. Different manufacturing modes, which can respond to market changes and social needs, are integrated by different manufacturing systems, product systems, and business models. The external driving force of each new manufacturing mode originates from market demands, social needs, and new enabling technologies, which make it possible to breed a new manufacturing mode.

2.2 Development of manufacturing mode

The tendency of digitization, networking, and intellectualization of manufacturing industry is irreversible. As shown in Fig. 2, the manufacturing paradigm has successively gone through mechanization, electrification, digital manufacturing, smart manufacturing, and intelligent manufacturing 2.0 [13]. The enabling technologies of mechanization and electrification brought about the first and second industrial revolutions, and the information technology is the main enabling technology for digital manufacturing, smart manufacturing, and intelligent manufacturing 2.0. The development of information technologies has experienced eras of PC, Internet, and mobile Internet and is under digital economy currently. Generally, the manufacturing paradigm is abstract, and the manufacturing mode is specific or concrete; therefore, a manufacturing mode can be regarded as an instance of manufacturing paradigm. Each manufacturing paradigm can breed many manufacturing modes, which are always related to market demands, social needs, and enabling technologies at that time.

(1) Mechanization manufacturing paradigm

![Fig. 1 Manufacturing mode model](image-url)
The mechanization manufacturing paradigm mainly refers to the manual manufacturing mode that the design, processing, assembly, and inspection are done manually by individuals; therefore, it is difficult to realize mass production.

(2) Electrification manufacturing paradigm

The electrification manufacturing paradigm mainly refers to the mass production manufacturing mode which is also known as Ford mass production. In this mode, most workplaces are fixed, and parts or processes are handled by a fixed number of steps. The production of high-quality standardized interchangeable parts is the main enabling technology for the success of this mode.

(3) Digital manufacturing paradigm

The digital manufacturing paradigm breeds various manufacturing modes such as lean manufacturing, flexible manufacturing, computer integrated manufacturing, agile manufacturing, and contemporary integrated manufacturing, and these different manufacturing modes are formed by different enabling technologies, market demands, and social needs.

(4) Smart manufacturing paradigm

The smart manufacturing paradigm consists of American industrial Internet, Germany’s industry 4.0, and China’s Internet Plus [14–17]. It is a digital and networked manufacturing mode essentially. It has a certain degree of intelligence and can realize universal communication and integration by industrial Internet and cloud.

(5) Intelligent manufacturing (2.0) paradigm

In summary, the digital manufacturing improves the efficiency and performance of the production process; the smart manufacturing extends service capability of products (American industrial Internet) and also improves the intelligence level of production process (Germany’s industry 4.0) and reshapes enterprise’s business model by introducing characteristics of open, equality, and interaction into manufacturing industry.

In the intelligent manufacturing 2.0 paradigm, manufacturing systems will develop into intelligent systems with HCP collaboration and fusion. Products and services will be integrated into a service-based ecosystem platform. The traditional business model centered on economy will transform into the sustainable business model which also gives consideration to environmental and social benefits.

2.3 The intelligent manufacturing mode with HCP collaboration and fusion for non-ferrous metal industry

As shown in Fig. 3, a new intelligent manufacturing mode with HCP collaboration and fusion for non-ferrous metal industry is constructed. The new manufacturing mode includes a service-based ecosystem platform, a sustainable business model, and an intelligent manufacturing system with HCP collaboration and fusion. The sustainable business model consists of three parts: economy, environment, and society. The intelligent manufacturing system with HCP collaboration and fusion will have abilities of intelligent perception, analysis, decision-making, self-control and self-learning; therefore, it can improve the utilization rate of resources and energy and reduce the production cost and environmental pollution. The service-based ecosystem platform can provide various value-added services centered on customers’ demands. The sustainable business model brings value proposition of sustainable development into enterprise’s strategy and examines enterprise’s transformation towards sustainability from economic, environmental, and social perspectives.
The key of the intelligent manufacturing system is the knowledge graph-based HCP data fusion system, the digital twin-based human-cyber collaborative analysis and decision-making system, and the human machine interface (HMI) and equipment autonomous control system. The knowledge graph-based HCP data fusion system can realize multi-domain data management uniformly and avoid inconsistent or incomplete information caused by information isolation in different domains. Therefore, it can improve the utilization rate of multi-domain data. The digital twin-based human-cyber collaborative analysis and decision-making system can realize cooperation between human and cyber system; it can improve reliability and collaboration ability of cyber-physical system (CPS) in the intelligent manufacturing system. The HMI and equipment autonomous control system can improve the efficiency of human–machine interaction by various interfaces such as voice user interface, graphical user interface, and dialogue user interface.

The service-based ecosystem platform integrates upstream suppliers and downstream customers. It can provide ample services, which can create new value for customers and bring new income to enterprises.

The sustainable business model incorporates the concept of sustainability into enterprise’s value proposition; it evaluates the enterprise’s value proposition from economic, environmental, and social perspective, which can make enterprise transform towards sustainable development.

In summary, the proposed manufacturing mode is a solution for the existing problems of non-ferrous metal industry.

3 The intelligent manufacturing system with HCP collaboration and fusion

Although there are some differences between traditional and intelligent manufacturing systems, their technical mechanism is the same, and both can be seen as human-cyber-physical system (HCPS). Furthermore, the traditional manufacturing system can be regarded as human-physical system (HPS), and the digital manufacturing system, smart
manufacturing system, and intelligent manufacturing system 2.0 can be regarded as HCPS1.0, HCPS1.5, and intelligent manufacturing system with HCP collaboration and fusion.

3.1 HPS

As shown in Fig. 4, in traditional manufacturing systems driven by HPS, the manual labor is replaced by machine. At this stage, operating the machine to finish various tasks totally relies on human because the information system has not yet appeared. The tasks of information perception, analysis, decision-making, and cognitive learning are all done by human; besides, these tasks are intensive and demanding so that manufacturing systems have limited ability to settle complex problems.

3.2 HCPS1.0 and HCPS1.5

Compared with the traditional manufacturing systems, manufacturing systems driven by HCPS1.0 and HCPS1.5 introduce an information system. The information system can replace humans to complete part of the brainwork; as a result, the manufacturing system’s abilities of perception, analysis, and control are greatly improved. As shown in Fig. 5, HCPS1.0, which is also known as digital manufacturing, is characterized by the wide application of information technology such as computers, communication, and digital control.

As shown in Fig. 6, the Internet and cloud platform are important components of manufacturing systems driven by HCPS1.5. At this stage, information exchange and sharing, integration, and optimization are the main features.

3.3 HCP collaboration and fusion

In the prior manufacturing systems such as computer integrated manufacturing system and flexible manufacturing system, the mechanism of human-cyber cooperation can be summarized as two aspects: (1) Humans endow knowledge to the cyber system, which works automatically under humans’ will and can’t generate new knowledge by itself. (2) Decisions are made jointly by human and cyber system, and cyber system is acted as an executor.

The information technologies such as IOT, big data, and NGIT enable HCP collaboration and fusion. In the era of HCP collaboration and fusion, the cyber system has the ability of self-learning and thus can replace human to complete the tasks of perception, analysis, and decision-making. Regardless of the stage of the manufacturing system, humans always play the dominant role and are the creators of cyber and physical systems.

As shown in Fig. 7, the intelligent manufacturing system with HCP collaboration and fusion consists of three parts: (1) the HMI and equipment autonomous control system, (2) the digital twin-based human-cyber collaborative analysis and decision-making system, and (3) the knowledge graph-based HCP data fusion system. The HMI and equipment autonomous control system includes intelligent
perception, intelligent analysis and decision-making, intelligent autonomous control, and the physical system. The digital twin-based human-cyber collaborative analysis and decision-making system consists of human-cyber collaborative learning promotion, accurate execution, independent decision-making, and real-time analysis based on the digital twin and the new generation of AI. The knowledge graph-based HCP data fusion system provides the fusion methods for the sensor data, product data, manufacturing data, management data, and abstract data from the physical system, cyber system, and human, respectively.

(1) Digital twin-based human-cyber collaborative analysis and decision-making

Under the background of large-scale customization, flexible production, part tracking, and product self-awareness of industry 4.0 and communication between machines and other products, field equipment, machines, factories, and individual products
will be connected to the network. As a key concept of industry 4.0, PS can be described as a group of physical devices, objects, and facilities that interact with virtual cyber space through a communication network. Each physical device takes its virtual cyber as the digital representation of its real device and finally forms a “digital twin.” The digital twin is like a virtual representation of physical products in a CPS, and a digital twin-based model contains all information and knowledge. Data transmission from the physical part to the network part can monitor and control physical entities, and physical entities can send data to update their virtual models. The digital twin model realizes the cooperation between humans and cyber in an intelligent manufacturing system. For example, the digital machine twin tool in equipment management integrates manufacturing data and sensing data into the digital twin model to improve the reliability and cooperation ability of CPS.

Therefore, a digital twin model in the non-ferrous metal industry is constructed, as shown in Fig. 8. By constructing various twin models of information space, such as simulation, mechanism, prediction, evaluation, optimization, and control, HCP coordination and iterative optimization in information space and physical space can be realized to integrate material flow, energy flow, and information flow and improve the intelligence degree of the manufacturing system.

The resource layer represents the bottom part of the stack. Resources include physical entities such as design and construction drawings, product process documents, raw materials, manufacturing equipment, production workshops, factories, and energy sources such as electricity and gas. The human can also be regarded as a part of resources. The resource layer represents the boundary of a large amount of data collection and control. Besides, it represents the software and hardware adapters connected to the machine, which are necessary to communicate with the upper layer.

The link layer provides communication and data connection services, including cloud infrastructure, cloud services, cloud storage, and network hardware.

The data layer represents the data communication with the resource layer. All kinds of resources from different domains, such as product, manufacturing, and management, have their own virtualization state. A database instance supports this virtualization. The database instance is constructed to receive real-time stream data from resources. The driver written on this data layer can communicate with the exclusive interface of a single machine. The knowledge map of different domains in the data layer is used for data analysis.

![Fig. 8 The digital twin model for non-ferrous metal industry](image)
and fusion. The heterogeneous data of product, manufacturing, management, and other subject domains are integrated to facilitate higher-level system call.

The model layer provides different model views of all kinds of resources. It provides resource location, status, simulation, mechanism, optimization evaluation, and so on, to support collaborative optimization and decision-making of the manufacturing system.

The function and service layer provides a variety of specific applications.

(2) Knowledge graph-based HCP data fusion

In the intelligent manufacturing system of non-ferrous metal industry, the data is from the products, production, and management domains, in which the data storage structures are not the same. Therefore, it is difficult to realize data sharing and fusion, to mine the relationship between different domain data, and to support the cross layer and domain collaborative optimization of the business process.

The multi-domain data of the manufacturing system can be divided into human-related data, cyber system-related data, and physical object-related data. Among them, human (human resource) has the advantage of incomplete information-based decision-making ability and the disadvantage of poor ability to acquire deep knowledge, the cyber system has the advantage of processing massive data and the disadvantage of poor ability to process incomplete information, and the physics system has the advantage of strong execution ability and the disadvantage of lack of strong data processing ability. How to effectively integrate these three types of heterogeneous data, build enterprise data space, realize data cross domain interconnection, and improve data utilization rate is an urgent problem to be solved.

The knowledge graph is often used to fuse multi-source data, which can consider the association and characteristics between multi-source data. A knowledge graph-based HCP data fusion framework provides technical support for cross layer and domain collaborative optimization, decision-making, and data fusion. As shown in Fig. 9, there are three steps to build the knowledge graph: (1) HCP object data acquisition; (2) HCP knowledge extraction; (3) HCP knowledge storage.

(3) Human–machine and human-cyber interface

In non-ferrous metal industry enterprises, decision-makers of remote management realize human-cyber-machine interaction through a voice user interface, graphical user interface, dialogue user interface, interactive touch interface, and three-dimensional interactive interface.

4 The service-based ecosystem platform

With the repaid development of information technologies, the product system has undergone profound innovations. Digital technologies such as IOT, Internet, big data analysis, and AI enrich functions of products and transform products into intelligent products with services and open up new markets. The speed of collaboration and response of intelligent products becomes more and more faster; besides, intelligent products can be transformed into a service-based ecosystem platform, which is an infrastructure to support interactions between different participants.

The transformation of products from single function to rich function means that profound changes have taken place in the software and equipment manufacturing industry. Successful platform will produce a network effect. With the increase number of the platform’s user and usage, the platform’s value will be added; in addition, the “economies of scale of the supplier” that originally depend on the expanding scale of manufacturing, procurement, and distribution will be transformed into “economies of scale of the demander” that depend on the scale and usage of users.

Product manufacturers need new technologies and services to provide value to customers the maximize product value. Few companies can independently provide all the components of intelligent products; therefore, companies have to cooperate with each other and participate into partner’s ecosystem and integrate products into a platform, an ecosystem, or service solutions so that products can be sold in the form of service.

4.1 Transform product structure from mechanical parts to digital accessories

The changes in source of value creation require manufacturers to reform their products radically. In recent decades, the sources of value creation have changed, and the proportion of software in products’ value has increased. It is expected that this tendency is more obvious in the process of product digitization. As shown in Fig. 10, at present, the distribution of source of product value is as follows: 40% software, 30% electronic devices, 20% mechanical parts, and 10% digital accessories. Digital accessories generally have the following functions with AI: big data acquisition and analysis, machine learning, intelligent voice assistant, and nature language processing. Therefore, it is estimated that the distribution of sources of product value in the future is as follows: 20% software, 5% electronic devices, 5% mechanical parts, and 70% digital accessories, which are necessary for fundamental product transformation.

As shown in Fig. 11, in the past, products were functional, and their structures included mechanical,
In the future, products which consist of data, services, user interfaces, and other parts will be experiential and can provide user-centered intelligent services.
4.2 Integrating products and services into a service-based ecosystem platform

When the intelligence and connectivity of a product have been improved, the user experience will also change. With the emerging of intelligent products, the economy dominated by product performance will gradually transform to an economy dominated by experience. The experience which is based on the sum of all interactions between consumers and companies providing products, services, or brands is highly personalized. Therefore, the experience is more difficult to design than the product, which often requires the full participation of users.

As shown in Fig. 12, the vertical axis describes the process of product reform and focuses on functions of the service and experience. At first, companies rely on value-added services to expand their production. These services can be basic services such as quality assurance and product support or complex data services based on Internet products. In the process of changing to the “product as a service” mode, there has been a major change that the enterprise is transformed from selling transactional products and services to market products and services to provide an end-to-end user experience. Some companies will experience considerable changes because they develop their products into a platform to connect with ecosystem partners. It is noteworthy that the notions customer experience and customer service should not be confused. The customer service is expected to help customers solve problems, submit complaints, provide feedback, and request certain content while the customer experience is more proactive and continuous. If the enterprise has reliable products and services especially with a strong customer experience, it may not need many customer service activities.

The horizontal axis reflects the development of product technology, which has successively experienced traditional products, Internet products, and independent products. Traditional products can be transformed into Internet products by adding sensors that generate and transmit data and into autonomous products by embedding AI technology. In this process, the product architecture and development process will undergo fundamental changes. Some concepts in Fig. 12 are explained as follows:

Traditional products and basic Internet products: The connectivity and user experience of products need to be improved to enter into new value space.

Internet product as a service: The business model is transformed from “transactional hardware sale” to “as a service,” which can improve the product experience.

Fig. 10 Evolution of product value

Fig. 11 Changes in product structure

| Structure of past products | Structure of future products |
|---------------------------|------------------------------|
| Functional                | Experiential                 |
| Mechanics                 | Data                         |
| Electronics               | Platforms and ecosystems     |
| Software                  | User interface in digital era |

Digital technology, connectivity, artificial intelligence……
Intelligent products: AI technology either is widely used as an embedded function or is applied by the edge and cloud network.

Intelligent service: Intelligent service combines intelligent product and service as a business model. With the advent of AI technology, large-scale customized and personalized services will become a reality, which will improve the value for customers.

Ecosystem platform: an ecosystem platform will completely change the business model. Whether building a platform or using a third-party platform to provide intelligent products or services, it can create value.

5 The sustainable business model innovation

The NGIT promotes enterprises to change their production system and manufacturing system. These changes can reduce costs and increase efficiency; moreover, it can also maintain its competitive advantages and seize new opportunities. However, it should be noted that the evolution of value creation cannot be ignored; therefore, to analyze this process from the perspective of BMI is necessary for realizing this transformation.

5.1 Business model concept

(1) Definition of business model

Over the years, the business model has been regarded as an indispensable tool in business activities, which can outline the process of enterprises’ value creation. Although a lot of research has been done on business models [18–20], the research of this field is still in its infancy. So far, there is no consistent definition for a business model. These studies use different terms to describe the elements of a business model, which include market segmentation, value proposition, value chain structure, value acquisition mechanism, and the relationship between the elements [21]. Most business model definitions are consistent with Teece’s: “the business model is the design or architecture of the value creation, transmission and acquisition mechanism it adopts” [22].

(2) Business model canvas

The business model canvas is the most commonly used form proposed by Alexander Osterwalder et al. to draw an enterprise’s business model [23]. It is a common language used to describe, visualize, evaluate, and change a business model. As shown in Fig. 13, the business model canvas consists of nine basic building blocks, covering four aspects: customer, provision (product/service), infrastructure, and financial viability. It can be used to describe and build new strategic alternatives. This canvas aims to analyze the business model from the economic point of view.

As shown in Fig. 14 and Fig. 15, Joyce et al. extended the business model canvas proposed by Osterwalder
et al. by adding the social layer and environmental layer [24]. The social business model canvas represents the relationship between stakeholders and enterprises. The environmental business model canvas is used to represent the environmental benefits of enterprises and the impact of products on the environment during its whole life cycle. Thus, these three business model canvases are tools for enterprises to innovate their business model for sustainable development.

5.2 BMI

BMI is often referred to as a process designed to reduce costs, optimize processes, enter new market, or improve financial performance [25, 26]. Compared with product and

---

**Fig. 13** Economic business model canvas

| Economic Business model Canvas |
|-------------------------------|
| Key partnerships | Key activities | Value proposition | Customer relationships | Customer segments |
| Key resources | Distribution channels |
| Costs structure | Revenue stream |

**Fig. 14** Social business model canvas

| Social Business model Canvas |
|-------------------------------|
| Local communities | Governance | Social value | Societal culture | End-user |
| Employees | Scale of outreach |
| Social impacts | Social benefits |

**Fig. 15** Environmental business model canvas

| Environment Business model Canvas |
|-------------------------------|
| Supplies and outsourcing | Production | Functional value | End-of-life | Use phase |
| Materials | Distribution |
| Environment impacts | Environment benefits |
process innovation. BMI is a systematic change that affects enterprises’ value proposition and ways of value creation. Some studies show that BMI is usually more successful than product or process innovation [27]. Generally, enterprises with the best business model rather than leading technology solutions dominate the market [28]. The BMI process is usually related to changes in the competitive environment or the emergence of new enabling technologies. New enabling technologies will have subversive impacts on the industry, which will breed new models, ecology, and development opportunities; meanwhile, it also brings new pressures and challenges to enterprises. Generally, enterprises that seize the opportunity to transformation will achieve great success, while enterprises that ignore the innovation are easily surpassed and eliminated.

At present, most of the research related to the impact of new enabling technologies on business model innovation is about industry 4.0, which is first proposed by Germany. The industry 4.0 aims to use an IOT-based information system to realize a fast and effective personalized product supply by digitizing the information of supply, manufacturing, and sale [29]. It can also improve the production efficiency of enterprises [30] and change the form of products [31]. It can connect with users and obtain their data which can be used to provide personalized or customized services. In addition, users can actively participate in the product design process. Some studies summarized the types of BMI in manufacturing industry 4.0. Dorleta divides the BMI into incremental and fundamental types [32]. The incremental innovation includes internal and external process optimization and customer interface improvement, and fundamental innovation includes new ecosystem, value networks, and intelligent products and services [33]. From the perspective of value creation, these innovations can be summarized into two types. The first type is that enterprises optimize the production efficiency of manufacturing systems through new enabling technologies and provide the highest level of output with the lowest amount of resources by continuously optimizing consumptions of resource and energy, which can obtain new values. The other is to provide new services or products for customers to create new value according to customer’s needs.

Although BMI under industry 4.0 has brought many benefits to enterprises, most enterprises studied belong to discrete industries. In contrast, non-ferrous metals enterprises belong to the process industry, which is very different from discrete industry. The demand for personalized customization of non-ferrous metal products is low, and products can’t be upgraded to “intelligent products”, which leads to the lack of high value-added services. Additionally, the production process of non-ferrous metals is long, and the utilization rate of resources and energy needs to be improved. The waste in the production process greatly damages the environment, and the environmental protection issue is prominent. To make the non-ferrous metal industry towards green and efficient development, it is necessary to study the sustainable business model of non-ferrous metals enterprises. The HCP collaboration and fusion, which is a new enabling technology, can be used for non-ferrous metals enterprises to realize BMI.

5.3 Sustainable business model in intelligent manufacturing mode

The intelligent manufacturing mode with HCP collaboration and fusion will improve the efficiency of manufacturing systems and reduce pollution emissions; besides, it can also increase the added value of products. These sustainable development practices make enterprises develop towards a green and efficient direction. From a strategic point of view, the connotation of green sustainable development needs to be reflected in the business model. As shown in Fig. 16, a BMI framework is built.

The benchmark is the traditional business model of non-ferrous metals enterprises, which doesn’t consider sustainability in the value proposition. The manufacturing system with HCP collaboration and fusion and service-based ecosystem platform will bring sustainable development practice to enterprises. The reformed sustainable business model represents the value proposition of green and efficient.

Fig. 16 The framework of BMI for non-ferrous metals enterprises
Proposition 1 (P1): The traditional business model represents the enterprise’s value proposition before BMI, which doesn’t take sustainability into consideration.

Proposition 2 (P2): BMI is a process of internalizing the external changes of enterprises’ competitive environment from a strategic point of view, which will change enterprises’ value proposition.

Proposition 3 (P3): The HCP collaboration and fusion enabling technology is an important external change factor in enterprises’ competitive environment, which can improve the production efficiency of enterprises and bring enterprises sustainable development practices.

Proposition 4 (P4): The practices such as some measures to reduce pollution or improve production efficiency, which are driven by HCP collaboration and fusion, are in line with the theme of sustainable development.

Proposition 5 (P5): The sustainable business model represents the new value proposition of enterprises, which incorporates sustainability into their value proposition and enables them develop towards a sustainable direction.

6 A case study on non-ferrous metal industry

The case study is based on the Jiangxi Copper Group founded in July 1979. It is a large-scale joint enterprise in China’s non-ferrous metal industry that integrates copper mining, beneficiation, metallurgy, and processing; besides, it is the largest production base of copper products and an important source of sulfur chemical raw materials such as gold, silver, and other rare metals. The company is headquartered in Nanchang, Jiangxi Province, China. Jiangxi Copper Group owns the first copper smelting enterprise in a flash furnace in China, which is the largest single copper processing plant and the largest copper and gold producer in China. Jiangxi Copper Group includes these firms: Guixi Smelter, Jiangxi copper (Qingyuan) Co., Ltd, and Zhejiang Jiangtong Fuye Heding Copper Co., Ltd. These companies have an annual output of 1.4–1.5 million tons of copper, 30 tons of gold, and 400 tons of silver.

To realize safe, efficient, and green production for the copper metal smelting process, an intelligent manufacturing mode with HCP collaboration and fusion is built from three aspects: (1) the intelligent manufacturing system with HCP collaboration and fusion, (2) the service-based ecosystem platform, (3) the sustainable business model.

6.1 The manufacturing system

As shown in Fig. 17, the intelligent manufacturing system with HCP collaboration and fusion in the non-ferrous metals enterprise covers multiple production bases, lines, and processes. It encompasses functions of supply chain management, production scheduling, quality control, logistic management, and decision-making. The system comprises an HMI and equipment autonomous control system, the digital twin-based remote management analysis and collaborative decision system, and the knowledge graph-based HCP data fusion system. The equipment autonomous control system has functions of intelligent perception, analysis, decision-making, and autonomous control. The digital twin-based remote management analysis and collaborative decision system supports the cross layer-domain optimal control of key processes, joint optimization of predictive maintenance and production scheduling, and integration plan of production, supply, and market. The knowledge graph-based HCP data fusion system provides data and information fusion components to support HCP integration in the cross layer-domain optimal control, predictive operation, and integrated plan.

Figure 18 describes a domain knowledge graph for the flash furnace production process, which depicts all entities and their relationships.

Compared with the traditional manufacturing system, the intelligent manufacturing system with HCP collaboration and fusion can optimize the whole process of copper smelting. When market demands or raw materials change, the whole process control of raw material procurement, business decision-making, planning and scheduling, process parameter selection, and production can achieve collaborative optimization to optimize the overall operation of the enterprise, reduce costs, and improve efficiency with the goal of high efficiency, controllable safety, and environmental protection.

The mechanism model is a kind of digital twin and has become the key to the HCP collaboration. Taking the flash furnace as an example, the real-time prediction of matte temperature, matte grade, and iron silicon ratio in slag can be realized by establishing the mechanism and data model. On this basis, the control flash furnace process can be optimized. Figure 19 shows the flash furnace melting model.

6.2 The framework of the service-based ecosystem platform

As shown in Fig. 20, the participants of the service-based ecosystem platform for the Jiangxi Copper Group include enterprises, customers, and partners. Partners are the main body that can provide services for customers outside the enterprises. The platform business includes four parts: non-ferrous metal products, product-related services, process-related services, and other services. Non-ferrous metal products are the enterprises’ traditional business, including main and subsidiary products. Other businesses of the platform are service-related and can bring value to customers.

Product-related services are supplements for products. Enterprises can provide product-related consulting services.
based on product experience. Process-related services are built on the internal processes of enterprises. Besides, enterprises can also provide external consulting services such as intelligent production and digital transformation.

Other services include some customized services or subscription services, which are provided according to customers’ needs.

6.3 The business model canvas

(1) Traditional business model

The economic business model canvas of the Jiangxi Copper Group before the reform is shown in Fig. 21. The company’s main partners are energy and resource suppliers, which include raw material suppliers, power suppliers, and equipment and machinery suppliers. In addition to suppliers supporting production, other partners provide IT solutions, logistics services, and financial services. The company’s main activities include procurement, marketing-related activities, process planning, smelting processing, and equipment operation and maintenance. There are some problems, such as the disconnection of production, supply, and marketing; the low degree of the intelligent production process; heavy pollution; and high failure rate of production equipment. The mine, smelting technology, and financial assets are main resources of the company. The company’s value proposition is to provide cost-effective non-ferrous metal products. The company’s customers are mainly distributed in deep processing industries such as wire materials and pipes and in application industries such as electric power and household appliances. The company’s income mainly depends on product sales and processing. The company relies on large-scale production to maintain a low-cost competitive advantage because non-ferrous metal products have serious homogenization and low added value.

(2) Sustainable business model

Economic business model canvas The economic business model canvas of the Jiangxi Copper Group after the reform
is shown in Fig. 22. The third-party service providers are added to the company’s main partners. The company’s service-based ecosystem platform can attract third-party service providers to settle in. The company and the third party jointly provide customer-centric services, and the demanders cover upstream suppliers and downstream customers. In terms of main activities, due to the introduction of HCP collaboration and fusion enabling technology, production, supply, and marketing activities can be integrated for optimization and decision-making. The main process can be optimized across layers, and equipment can be maintained and managed predictably, which will reduce production costs and improve production efficiency. In terms of main resources, a service-based ecosystem platform has been
added. The customer-centric services are added to the value proposition. The third-party service provider is a partnership with the company. The company’s revenue will not be limited to the sales and processing fees of non-ferrous metal products. The service-based ecosystem platform will bring service fees and commission income to the company.

**Environmental business model canvas** The environmental business model canvas of Jiangxi Copper Group after innovation is shown in Fig. 23, which represents the company’s environmental impact during product’s life cycle. In addition, this canvas can show the company’s sustainable
practice in energy conservation, environmental protection, and circular economy.

The function value represents the impact of annual copper production on the environment. The sustainable practice driven by HCP collaboration and fusion enabling technology has brought the following benefits related to energy conservation, environmental protection, and circular economy.

Waste heat power generation: The flue gas waste heat resources are comprehensively recycled, and the annual power generation capacity of waste heat exceeds 200 million degrees.

Industrial water circulation: The utilization rate of industrial water circulation is more than 92%; the water-saving amount is equivalent to one West Lake a week.

Waste rock heap leaching: Build the first waste rock heap leaching extraction electro-winning plant in China, and recover more than 1000 tons of copper every year.

Acid production from flue gas: The largest acid production plant from smelting flue gas in China has been

---

### Economic Business model Canvas

| Key partnerships | Key activities | Value proposition | Customer relationships | Customer segments |
|------------------|----------------|-------------------|------------------------|-------------------|
| 1) Raw material suppliers  
2) Plant and machinery suppliers  
3) Suppliers of electricity  
4) IT solution providers  
5) Logistics service provider  
6) Financial services providers  
7) Third party service provider | 1) Intelligent purchasing, marketing and sales  
2) Intelligent smelting and processing  
3) Predictive maintenance and management of equipment  
4) Operate service platform and service provision | 1) Provide cost-effective non-ferrous metal products  
2) Provide customer-centric service | 1) Supply relationship  
2) Partners | 1) Deep processing industry customers (wire, pipe, etc.)  
2) Application industry customers (electric power, home appliances, etc.)  
3) Customers with demand for platform services |

| Key resources | Distribution channels |
|----------------|-----------------------|
| 1) Mine  
2) Smelting technology  
3) Financial assets  
4) Ecosystem service platform | 1) Offline sales network  
2) Online sales network |

| Costs structure | Revenue stream |
|-----------------|---------------|
| 1) Manufacturing costs  
2) Research & development costs  
3) Equipment maintenance and management  
4) Platform maintenance and management | 1) Product sales  
2) Product processing  
3) Service charge  
4) Platform commission |

---

**Fig. 22** The economic business model canvas of Jiangxi Copper Group (after BMI)

---

### Environment Business model Canvas

| Supplies and out-sourcing | Production | Functional value | End-of-life | Use phase |
|---------------------------|------------|------------------|-------------|-----------|
| 1) Electricity  
2) Water  
3) Methane  
4) Laboratory equipment  
5) Laboratory consumables | 1) Melting process  
2) Blowing process  
3) Refining process  
4) Electrolysis process | 1) One ton of copper multiplied by one ton of copper in a year total output | 1) Copper scrap disposal | 1) Maintenance |

| Materials | Distribution |
|-----------|--------------|
| 1) Copper concentrate  
2) Quartz sand  
3) Slag concentrate  
4) Ingredients | 1) Truck transport  
2) Shipping  
3) Train transportation |

| Environment impacts | Environment benefits |
|---------------------|----------------------|
| 1) Air pollution  
2) Soil pollution  
3) Water pollution | 1) Industrial water cycle  
2) Heap leaching of waste rock  
3) Acid production from flue gas  
4) Copper extraction from wastewater  
5) Copper separation from waste residue  
6) Waste heat power generation  
7) Energy saving and environmental protection |

---

**Fig. 23** The environmental business model canvas of Jiangxi Copper Group (after BMI)
Social Business model Canvas

| Local communities | Governance | Social value | Societal culture | End-user |
|------------------|------------|--------------|-----------------|---------|
| 1) Staff         | 1) State owned enterprises | 1) Provide customers with quality products | 1) Fulfill social responsibility | 1) High quality products |
| 2) Supplier      | 2) Functional specialization   | 2) Continuously tap the value of resources |       | 2) Environmental protection products |
| 3) Trade channel | 3) Transparent communication | 3) The pursuit of harmonious coexistence between human and nature |       | 3) Cost effective products |
| 4) Trade union   | | | | |
| 5) Customers     | | | | |
| 6) Media         | | | | |
| 7) Competitors   | | | | |

Employees

- 1) Local labor force
- 2) High recruitment rate
- 3) Low turnover rate

Scale of outreach

1) Global sales network
2) Long term relationship with domestic suppliers
3) Long term relationship with international suppliers

Social impacts

1) Pollution caused by production process

Social benefits

1) Job creation
2) Increase local revenue
3) Social welfare

Fig. 24 The social business model canvas of Jiangxi Copper Group (after BMI)

Built, with a total sulfur utilization rate of more than 97%, reaching the top level globally.

Copper extraction from wastewater: More than 1000 tons of copper are recovered from wastewater every year, and more than 20,000 tons of wastewater are purified and treated every day.

Copper separation from slag: Make full use of resources in smelting slag and recover valuable elements. More than 9000 tons of copper metals are recovered from smelting slag every year, which is equivalent to the output of the annual metal of a medium-sized copper mine in China.

Social business model canvas The canvas of the social business model of Jiangxi Copper Group after reform is shown in Fig. 24. This canvas model aims to investigate the interaction between the company’s stakeholders and the company and capture the social impact of these key relationships.

The social value generated by the company includes providing high-quality products for customers, continuously excavating the value of resources and pursuing the harmonious coexistence of humans and nature. In addition, the manufacturing system of HCP collaboration and fusion can bring high-quality, environmental protection, and cost-effective products, and the service-based ecosystem platform can create more employment opportunities and increase local fiscal revenue.

7 Conclusion and future work

Given the existing problems of the non-ferrous metal industry and the development of information enabling technology, this paper discusses the demand for transforming the non-ferrous metal industry’s manufacturing mode. A new manufacturing mode of non-ferrous metal industry in the era of intelligent manufacturing 2.0 is put forward, which is the intelligent manufacturing mode with HCP collaboration and confusion. It includes an intelligent manufacturing system based on HCP collaboration and confusion, a service-based ecosystem platform, and a sustainable business model. The intelligent manufacturing system with HCP collaboration and confusion can improve production efficiency and reduce environmental pollution. The service-based platform can provide customer-centered service, and a sustainable business model can qualitatively and quantitatively describe the sustainable change process of the manufacturing system. Therefore, the new manufacturing mode can make non-ferrous metals enterprises develop towards green, efficient, and sustainable. Finally, combined with the largest copper smelting enterprise in the world (Jiangxi Copper), the corresponding architecture of manufacturing system, framework of product system, and business model driven by the new manufacturing mode are given, respectively.

The research of this paper is based on the case of non-ferrous metals enterprises. Next, the new manufacturing mode proposed in this paper will be used to other manufacturing enterprises.
Author contribution Qing Liu: Writing—original draft, writing—review and editing, investigation, methodology, experiments conduction.
Min Liu: Writing—review and editing, project administration, methodology.
Zichun Wang: Investigation, software development, visualization, data analysis, validation of the software tools.
Feng Yan: Experiments conduction.
Yingyi Ma: Experiments conduction.
Weiming Shen: Advice and supervision.

Funding This work was supported partly by the National Key R&D Program of China under 2019YFB1704700 and partly by the Natural Science Foundation of China under 71690234.

Data availability Data sharing is not applicable to this article.

Code availability Code availability is applicable by the website on http://61.149.254.174:3889/login (uid:ysy/psw:111,111).

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Yuan X, Gui W, Chen X, et al (2018) Transforming and upgrading nonferrous metal industry with artificial intelligence. Chinese J Eng Sci 20:59. https://doi.org/10.15302/j-sscae-2018.04.010
2. Ahmad T, Zhang D, Huang C et al (2021) Artificial intelligence in sustainable energy industry: status quo, challenges and opportunities. J Clean Prod 289:125834. https://doi.org/10.1016/j.jclepro.2021.125834
3. Haenlein M, Kaplan A (2019) A brief history of artificial intelligence: on the past, present, and future of artificial intelligence. Calif Manage Rev 61:5–14. https://doi.org/10.1177/0008125619864925
4. Wu F, Lu C, Zhu M et al (2020) Towards a new generation of artificial intelligence in China. Nat Mach Intell 2:312–316. https://doi.org/10.1038/s42256-020-0183-4
5. Mosenia A, Jha NK (2017) A comprehensive study of security of internet-of-things. IEEE Trans Emerg Top Comput 5:586–602. https://doi.org/10.1109/TETC.2016.2606384
6. Sisinni E, Saifullah A, Han S et al (2018) Industrial internet of things: challenges, opportunities, and directions. IEEE Trans Ind Informatics 14:4724–4734. https://doi.org/10.1109/TII.2018.2852491
7. Varghese B, Buyya R (2018) Next generation cloud computing: new trends and research directions. Futur Gener Comput Syst 79:849–861. https://doi.org/10.1016/j.future.2017.09.020
8. Ren J, Yu G, He Y, Li GY (2019) Collaborative cloud and edge computing for latency minimization. IEEE Trans Veh Technol 68:5031–5044. https://doi.org/10.1109/TVT.2019.2904244
9. Iqbal R, Doctor F, More B et al (2020) Big data analytics: computational intelligence techniques and application areas. Technol Forecast Soc Change 153:1. https://doi.org/10.1016/j.techfore.2018.03.024
10. Cui Y, Kara S, Chan KC (2020) Manufacturing big data ecosystem: a systematic literature review. Robot Comput Integr Manuf 62:101861. https://doi.org/10.1016/j.rcim.2019.101861
11. Tao F, Zhang H, Liu A, Nee AYC (2019) Digital twin in industry: state-of-the-art. IEEE Trans Ind Informatics 15:2405–2415. https://doi.org/10.1109/TII.2018.2873186
12. Koren Y (2010) The global manufacturing revolution: product-process-business integration and reconﬁgurable systems. John Wiley & Sons
13. Zhou J, Li P, Zhou Y et al (2018) Toward new-generation intelligent manufacturing. Engineering 4:11–20. https://doi.org/10.1016/j.eng.2018.01.002
14. Aazam M, Zeadally S, Harras KA (2018) Deploying fog computing in industrial internet of things and industry 4.0. IEEE Trans Ind Informatics 14:4674–4682. https://doi.org/10.1109/TII.2018.2855198
15. Boys H, Hallaq B, Cunningham J, Watson T (2018) The industrial internet of things (IoT): an analysis framework. Comput Ind 101:1–12. https://doi.org/10.1016/j.compind.2018.04.015
16. Beier G, Ullrich A, Niehoff S, et al (2020) Industry 4.0: how it is defined from a sociotechnical perspective and how much sustainability it includes – a literature review. J Clean Prod 259:120856. https://doi.org/10.1016/j.jclepro.2020.120856
17. Ghobakhloo M (2020) Industry 4.0, digitization, and opportunities for sustainability. J Clean Prod 252:119869. https://doi.org/10.1016/j.jclepro.2019.119869
18. Keiningham T, Aksoy L, Bruce HL et al (2020) Customer experience driven business model innovation. J Bus Res 116:431–440. https://doi.org/10.1016/j.jbusres.2019.08.003
19. Laukkonen M, Tura N (2020) The potential of sharing economy business models for sustainable value creation. J Clean Prod 253:120004. https://doi.org/10.1016/j.jclepro.2020.120004
20. Savolainen J, Collan M (2020) How additive manufacturing technology changes business models? – review of literature. Addit Manuf 32:101070. https://doi.org/10.1016/j.addma.2020.101070
21. Saebi T, Lien L, Foss NJ (2017) What drives business model adaptation? The impact of opportunities, threats and strategic orientation. Long Range Plann 50:567–581. https://doi.org/10.1016/j.lrp.2016.06.006
22. Teece DJ (2010) Business models, business strategy and innovation. Long Range Plann 43:172–194. https://doi.org/10.1016/j.lrp.2009.07.003
23. Parry Z (2014) Book review: business model generation: a handbook for visionaries, game changers, and challengers. Int J Entrep Innov 15:137–138. https://doi.org/10.5367/iiei.2014.0149
24. Joyce A, Paquin RL (2016) The triple layered business model canvas: a tool to design more sustainable business models. J Clean Prod 135:1474–1486. https://doi.org/10.1016/j.jclepro.2016.06.067
25. Wirtz BW, Pistoia A, Ullrich S, Göttel V (2016) Business models: origin, development and future research perspectives. Long Range Plann 49:36–54. https://doi.org/10.1016/j.lrp.2015.04.001
26. Foss NJ, Saebi T (2017) Fifteen years of research on business model innovation. J Manage 43:200–227. https://doi.org/10.1177/0149206316675927
27. Li F (2020) The digital transformation of business models in the creative industries: a holistic framework and emerging trends. Technovation 92–93:102012. https://doi.org/10.1016/j.technovation.2017.12.004
28. Chesbrough H (2010) Business model innovation: opportunities and barriers. Long Range Plann 43:354–363. https://doi.org/10.1016/j.lrp.2009.07.010
29. Frank AG, Dalenogare LS, Ayala NF (2019) Industry 4.0 technologies: implementation patterns in manufacturing companies.
30. Rojko A (2017) Industry 4.0 concept: background and overview. Int J Interact Mob Technol 11:77–90. https://doi.org/10.3991/ijim.v11i5.7072

31. Ślusarczyk B, Haseeb M, Hussain HI (2019) Fourth industrial revolution: a way forward to attain better performance in the textile industry. Eng Manag Prod Serv 11:52–69. https://doi.org/10.2478/emj-2019-0011

32. Ibarra D, Ganzarain J, Igartua JJ (2018) Business model innovation through industry 4.0: a review. Procedia Manuf 22:4–10. https://doi.org/10.1016/j.promfg.2018.03.002

33. Beverungen D, Müller O, Matzner M et al (2019) Conceptualizing smart service systems Electron Mark 29:7–18. https://doi.org/10.1007/s12525-017-0270-5

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.