DOI 10.15302/J-SSCAE-2018.04.009

Smart and Optimal Manufacturing for Process Industries

Chai Tianyou[1,2], Ding Jinliang[1], Wang Liangyong[1]

1. State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China
2. National Engineering Technology Research Center for Metallrugical Industry Automation, Northeastern University, Shenyang 110819, China

Abstract: We propose a new mode of intelligent manufacturing for the process industries, that is, smart and optimal manufacturing. Our mode is based on an in-depth analysis of the process industry and its state-of-the-art operation control as well as the global development of intelligent manufacturing. We analyze the development of the existing three-tier architecture (consisting of enterprise resource planning, manufacturing execution, and process control) and the control and management informatization adopted by process enterprises. We present a smart and optimal manufacturing framework and the prospects for future process enterprises as well as the key generic technologies critical for the deployment of intelligent manufacturing. We also present the fundamental challenges and scientific problems to be addressed jointly by automation, computer and communication, and data science. Lastly, we offer suggestions for the future development and deployment of smart and optimal manufacturing, emphasizing the strategic position of the process industries and actualizing strategic planning and top-level design.

Keywords: process industries; smart and optimal manufacturing; development vision; scientific challenges

1 Introduction

Process industries are an important component of the manufacturing industries, playing a significant role in economic and social development. They include industries related to petrochemicals, chemicals, iron and steel, non-ferrous metals, building materials, and power generation. Process industries are a significant support mechanism for the sustained growth of the Chinese economy. They use both raw and recyclable resources for raw materials, supplying the required material and energy for the manufacturing industries through continuous and complex production processes with gas-liquid-solid multiphase coexistence and relevant physical and chemical reactions. In the recent decades, China's manufacturing industries have been developing rapidly, increasing significantly in overall scale and continuously enhancing in comprehensive strength. Thus, the production technology, facilities, and automation of the process industry have been greatly improved, making China the country with the most comprehensive set of categories and largest process manufacturing scale in the world. The process industry in China is highly concentrated, and China has the largest production capacity worldwide for a number of industries, including power generation, cement, steel, nonferrous metals, and papermaking. On the other hand, the mineral resources in China present problems such as poor quality, low grade, difficult handling, and mixed composition as well as a depletion trend. This has led to an inefficient usage rate, long procedures, and high cost of mineral processing.

Shortage of resources, high-energy consumption, and serious environmental pollution are obvious bottlenecks restricting development of the process industry of China. In order to solve the resources, energy, and environmental protection problems, the

Received date: July 4, 2018; **Revised date:** August 13, 2018

Corresponding author: Chai Tianyou, Northeastern University, Professor; Chinese Academy of Engineering, Academician. Main research fields include theory, technology and application of industrial process synthetical automation system. E-mail: tychai@mail.neu.edu.cn

Funding program: CAE Advisory Project "Research on Development Strategy for 'Internet Plus' Action Plan" (2016-ZD-03); CAE Advisory Project "Research on Intelligent Manufacturing Led by New-Generation Artificial Intelligence" (2017-ZD-08-03)

Chinese version: Strategic Study of CAE 2018, 20 (4): 051–058

Cited item: Chai Tianyou et al. Smart and Optimal Manufacturing for Process Industries. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2018.04.009

Chinese process industries gradually adopted modern methods involving characteristics of the whole process and fine production, rather than the traditional process, that is, the production style of partial and extensive production. Thus, the utilization of resources could be enhanced and pollution could be reduced. Efficiency and green production are the inevitable research directions for China's process industry.

At present, several developed countries have adopted the "re-industrialization" strategy to vitalize their innovation and reshape their new competitive advantages in manufacturing, while some developing countries have also accelerated their planning and design to actively participate in the global redeployment of industrial labor and move into a favorable position in the new round of competition. From the perspective of global industrial development, developed countries use their superiority in information technology to accelerate their advances in the manufacturing industry. For instance, the US Smart Manufacturing Leadership Coalition proposed the 21st century "smart process manufacturing" technology framework with relevant roadmaps [1] for industrial upgrading through the integration of knowledge in production process optimization, involving the integration of knowledge with a large number of models using active response and protective strategies for optimal decision making in manufacturing. Germany claimed that the development strategy for the fourth industrial revolution was mainly based on intelligent manufacturing for the discrete manufacturing industry [2], the "Industry 4.0" plan. This plan used cyber-physics systems (CPS) to comprehensively integrate and coordinate computing and physical resources of the manufacturing process for the seamless integration and collaboration between products, equipment, labor, and organizations. Note that "Smart Factory" and "Smart Production" are the two themes of the Industry 4.0 plan. In this context, the Industry 4.0 achieves horizontal integration between enterprises through the value chain and information physics networks, and supports the development of new business strategies and models. The Industry 4.0 also carries out end-to-end integration throughout the value chain for full life-cycle management of product development and manufacturing with production and services. Moreover, Industry 4.0 is believed to automatically build resource configurations based on individual requirements to achieve networked manufacturing with vertical integration, flexibility, and recombination and enable high-efficiency customization. In addition, the United Kingdom has announced the "British Industrial 2050 Strategy," while Japan and South Korea have successively introduced their "I-Japan Strategy" and "Manufacturing Innovation 3.0 Strategy," respectively. Faced with these new changes in global industrial competition under the Fourth Industrial Revolution, China has come up with its "China Manufacturing 2025" initiative to capture the dominance of the future industrial competition.

Indeed, smart manufacturing has been recognized as the core technology-intensive activity that enhances the overall competitiveness of the manufacturing industry. Smart manufacturing is also the main tool for China to become a high manufacturing power. However, it can achieve a breakthrough in the manufacturing industry only through intensive research on new functional systems and achieving its targets through closely integrated characteristics and goals of manufacturing, and by making full use of big data, integrating and coordinating the physical resources of the manufacturing processes and information technologies such as artificial intelligence (AI), mobile Internet, mobile computing, modeling, control, and optimization.

2 The new pattern of smart manufacturing industries

In this section, we discuss a possible new trend of smart manufacturing industries in China taking into account the characteristics of process industries, and consider a number of related issues.

2.1 Problems in the existing operational pattern of process industries in China

In recent years, most of the large- and middle-sized process industries have adopted informatization-based construction. Process control has widely adopted the distributed control system (DCS), fieldbus control system (FCS), and programmable logic controller (PLC) system, installing advanced control software such as the emergency shutdown (ESD) system, advanced process control (APC) system, and real-time optimization (RTO) and operational control system, to realize closed-loop control, process monitoring, and optimal operation of the concerned production processes. The management decision system, enterprise resource planning (ERP) system, manufacturing execution system (MES), supply chain system, and energy management system are also employed in planning and management as well as operation and management of the production process. However, the decision analysis of the above planning and management and operation and management system of the production process have been found to depend only on the knowledge and experience of the knowledge workers, because the raw materials vary frequently and the working status fluctuates tempestuously in China's process industry. Furthermore, the production process involves physical and chemical reactions, involving a complicated mechanism. Moreover, the production is continuous and cannot be interrupted; also, a problem in any process will inevitably affect the whole production, and the final product quality, the composition of raw material, equipment status, technical parameters, and product quality cannot be comprehensively detected in real time. In addition, the optimal decision making of an industrial system consists of solving worldwide recognized scientific challenges, such as multiple conflicting objective optimization, constraints, and multi-scale dynamic optimization. The limitation of human behavior [3] makes it difficult to respond appropriately to the variations in market and production conditions. Thus, we have the following problems ranging from the production process to operational and management processes of industrial enterprises.

(1) Management decision layer based on capital flow: This constitutes a challenge in terms of lack of adaptation between supply chain procurement and equipment performance, the mismatch between product chain distributing and market demand, and lack of fast and accurate decision making on adapting to the changes in market and production conditions.

(2) Production and operation layer based on material flow: This represents a problem in terms of the lack of comprehensive utilization of resources and waste, the lack of refinement for operational management and operation, the lack of cooperative optimization for the various production processes in the whole production chain, the lack of real-time and accurate recognition of operating conditions, and the lack of real-time product quality monitoring and prediction.

(3) Security environment layer based on energy flow: This prompts a problem in terms of lack of real-time monitoring, prediction and optimal decision making on energy consumption in the whole production process; lack of real-time monitoring and tracking of wastewater, gas, and solids in the whole production life cycle; lack of real-time monitoring and early warning on storage and transportation of dangerous cargo and the key positions related to safety.

(4) The perception, cognition, and decision making layer based on information flow: This is a challenge in terms of delay in obtaining the material attributes and technical parameters of production. The dynamic characteristics, optimization operation, and knowledge of the production process are difficult to be extracted, making it difficult to integrate the planning and scheduling, decision making and control, and the seamless optimization of ERP, MES, and PCS. Thus, the industry's global optimization cannot be realized.

(5) System support layer: It is not easy to deal with big industrial data consisting of a large amount of production process data, text information, and images and sounds using DCS, PLC, and an operation and production management computer adopting equipment network, control network, and management network. Therefore, it is difficult to intelligentize the production process control and management systems.

From the above discussions, we find that the automation and informatization of China's process industries currently focus on automation of the transformation process of industrial devices and informatization of enterprise management, but lack in research activities on automation and intelligentization of knowledge work in process design, resource planning, and operation management of the production process.

2.2 Smart manufacturing of process industries needs new innovation pattern

The manufacturing industry includes discrete industries, such as machinery and equipment manufacturing, and process industries, such as important raw material processing industries represented by petrochemicals, metallurgy, building materials, and energy industry—for example, power generation.

Process industries and discrete manufacturing are obviously different, as shown in Fig. 1. The main process of discrete manufacturing can be summarized as the overall design of manufacturing equipment, processing equipment parts, and assembling manufacturing equipment. Processing and assembling parts are separate physical processes, and the products and processes can be digitized. Therefore, digital design and production can be realized through computer integrated manufacturing technology. The key is to optimize the overall design of manufacturing equipment. As for discrete manufacturing, the development goal of smart manufacturing is to efficiently achieve personalized custom-made equipment. On the other hand, the major product of the process industry is raw material, which is processed into various equipment along the production line through physical and chemical reactions in the flow of information and energy, and change of material flow, to form qualified products. In this context, the process and product are relatively fixed, and the product cannot be measured in one piece. Moreover, product processing cannot be divided in discretized ways. If the product

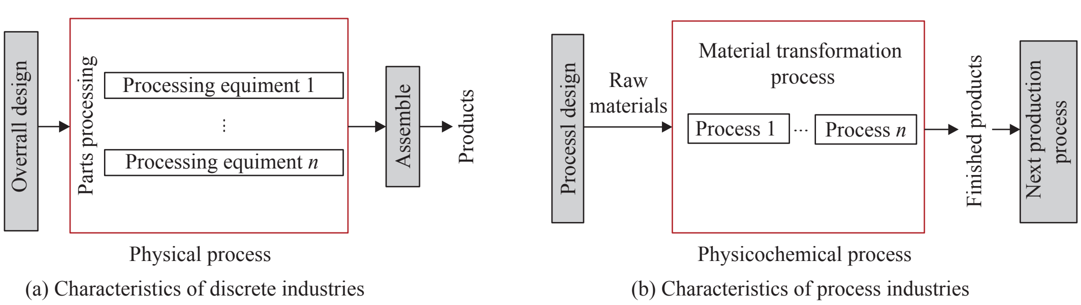

Fig. 1. Structure of discrete and process industries.

processing in one process of the production line has problems, such problems would affect the final product of the production line.

The key difficulty of the process industry is optimization of the process design and overall production process. Production optimization of the process industry consists of the following two tasks. ① Optimization of the existing production process to achieve high efficiency and green production throughout the production process. ② Development of an advanced production process for high performance and high value-added products. Overall optimization of the production process refers to the achievement of high efficiency and green production under changing global market demand and variation in unprocessed materials. It consists of unprocessed material purchasing, management decision making, plan scheduling, process parameter selection, and control of the whole production process to achieve seamless integration and optimization such that the enterprise optimizes the overall operation and realizes optimal control of the comprehensive production indices to form the parameters representing production quality and efficiency [4].

Therefore, the goal of smart manufacturing in the process industry is to achieve high efficiency and green production. The meaning of high efficiency is optimal control of product quality, production output, cost, and consumption in response to the variations in market and unprocessed materials, with safe and reliable operation of the whole production and manufacture process to achieve high performance and value-added products, maximizing the total profit of enterprises. The meaning of green production is efficient utilization of energy and resources, minimum consumption of energy and resources, zero emission of pollutants, and environment greening [4].

The key to high efficiency and green production of smart optimal manufacturing is optimization of the industrial art of production and overall optimization of the production chain. The process industry consists of a production process involving numerous major equipment difficult to model and digitalize because of the complex dynamic mechanism of the operational process. The diverse sources of unprocessed material, complex components, various production conditions, and frequent fluctuations in operating conditions generally make it difficult to optimize the industrial art of production and control of the entire production process [5]. Therefore, the Chinese process industry cannot adopt the discrete smart manufacturing pattern represented by Industry 4.0, and must therefore independently innovate the smart manufacturing pattern suitable for them to achieve high efficiency and green production. The process industry's smart manufacturing pattern is in fact smart optimal manufacturing, that is, intelligent optimal manufacturing of the process industry. Intelligent optimal manufacturing is based on the goal of high efficiency and green production in the enterprise and the whole production process and its operation, where the manufacturing mode is characterized by intelligent optimization of the industrial art of production and overall intelligent optimization of the entire production process.

3 System architecture and prospective function of smart optimal manufacturing for process industries

3.1 Architecture of smart optimal manufacturing system in process industries

The process industry currently uses a three-layered architecture consisting of the ERP, MES, and PCS, as shown in Fig. 2. While the ERP plans the resources of the enterprise, such as people, money, material, and energy, and monitors the information on plan completion, the MES plans the production and process parameters of each production department through production scheduling and industrial art design, decomposing them into a production line scheduling plan and process control operation index system. It monitors the completion information process parameters, scheduling plan, and operation indices. Thus, the main function of ERP and MES is information integration and management [6]. The decision analysis and adjustment of the enterprise goal, resource plan, scheduling plan, operation index, production instruction, and control instruction are mainly carried out by knowledge workers based on their knowledge and experience. Thus, the integration of the production planning decision and scheduling and process control, or the seamless integrated optimization of ERP, MES, and PCS, cannot be achieved.

The goal of the PCS is the closed-loop control of each industrial process loop, the logical control of each industrial equipment constituting the industrial process, and monitoring of the control process. The set points of the PCS, the production instruction, and operation condition identification still depend on the knowledge worker's knowledge and experience. The coordinated optimization of all the industrial PCSs of the whole production process cannot be realized. It is not possible to integrate the decision and control, optimize control of the whole

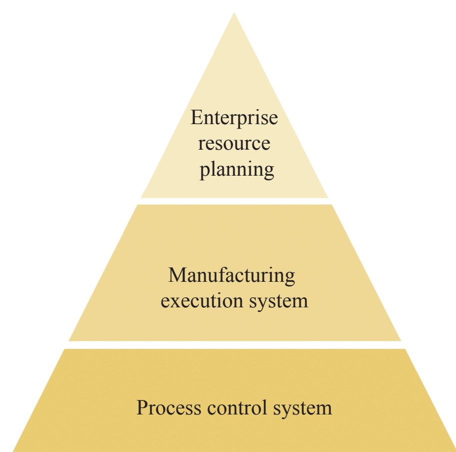

Fig. 2. Three-tier architecture of the process industry.

production process, and seamlessly integrate the optimization of ERP, MES, and PCS [7].

As pointed out in [8], AI is not a single technique, but a set of technologies applied to a particular task. As stated in [9], the definition of AI is unclear and constantly changing over time, but the research and application of AI has been based on a core goal for many years, namely, automation or replication of intelligent human behavior. Although the AI technology has no uniform definition, the purpose of AI technology is to enhance the ability of humans to understand and transform real-world issues by extending and enhancing the functions of human perception, cognition, decision making, and execution through machine intelligence in order to accomplish specific tasks that humans cannot complement, or to accomplish specific tasks more effectively than humans [10]. The development direction of intelligent manufacturing in the process industry is to combine the AI technology with ERP, MES, and PCS, improve the intelligence level of ERP, MES, and PCS, and then achieve the seamless integration and optimization of ERP, MES, and PCS.

In this scenario, the future process industry can adopt a two-layered architecture composed of an intelligence optimization decision system of human–machine cooperation and the intelligent autonomous control system of the industrial process, as shown in Fig. 3. The former adds the following three features to the functionalities of ERP and MES. ① Real-time perception of market information, production conditions, and operating conditions of manufacturing processes. ② Integrated optimal decision-making for enterprise goal, production planning, and scheduling through human–machine cooperation. ③ Remote, mobile, and visual monitoring of decision making and execution processes. The functionalities of PCS add the following four main features to the intelligent autonomous control system of the industrial process. ① Perception of changes in production conditions and operating conditions. ② Dynamic performance of the control system with change of the control systems' set points, frequent disturbance, and change in working condition. ③ Remote, mobile, and visual monitoring of operation conditions and self-optimization control. ④ Cooperating with other industrial PCSs in the whole production process and optimal control of the production indices.

3.2 Prospective functions of the smart optimal manufacturing system

3.2.1 Prospective functions of human-machine cooperation of the intelligent optimization decision system

Process enterprises presently adopt a two-layered architecture consisting of EPR and MES (Fig. 4), and manage the business operations and production processes via the information management system. This system includes the business decision, resource planning, manufacturing execution, supply chain, and energy management systems, and constitutes the information-based platform for decision making and business and production management analysis. The decision making and analysis depend on the knowledge workers' knowledge and experience.

The purpose of raising the intelligence level of the above information management system is to make it an intelligent optimization decision system of man−machine cooperation, as shown in Fig. 5. The system consists of three subsystems, intelligent optimization decision making, virtual manufacturing process and operational condition cognition, and self-optimization control. The human−machine cooperative intelligent optimization decision system has four major functions as follows. ① Re-

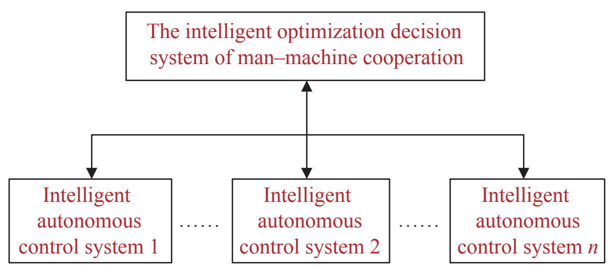

Fig. 3. Framework of the smart optimal manufacturing system for process industries.

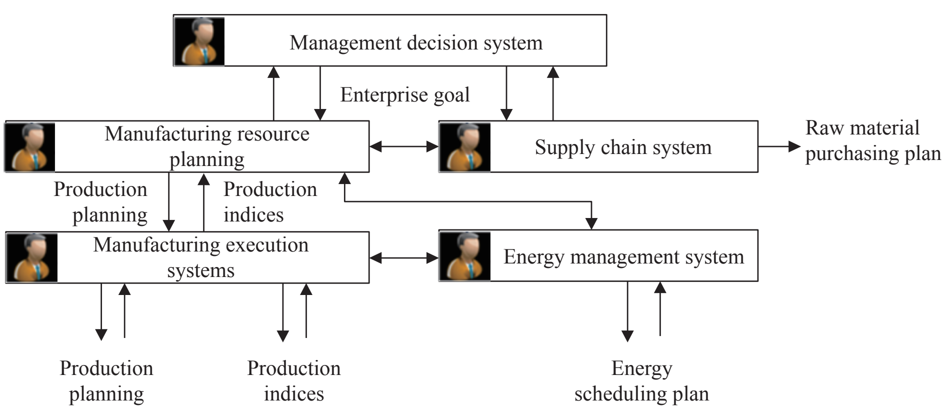

Fig. 4. Information management system.

al-time perception of market information, production conditions, and manufacturing process operating conditions. ② The goal of high efficiency and green production of enterprises involving the integrated optimization decision of the company's goals, planning and scheduling, operation indices, production orders, and control system set points. ③ Remote and mobile visual monitoring of dynamic performance of the decision-making process. ④ Self-learning and self-optimization in decision-making processes, cooperation between the human and intelligent optimization decision systems, and accurate optimization decision of the decision maker under the dynamic changing environment of the process.

3.2.2 Prospective function of intelligent autonomous control system for industrial processes

Presently, an advanced computer control system, such as the DCS or PLC, is used for the automatic control of industrial processes in advanced processing enterprises worldwide. Since petrochemical industries can establish mathematical models, the set points of the process control can be optimized through real-time optimization (RTO) and model predictive control (MPC). However, for complex industrial processes such as those in the metallurgical industry, the set points of the control system depend on the knowledge and experience of the knowledge workers. Currently, the diagnosis of abnormal operating conditions still depends on the knowledge workers' knowledge and experience [11].

The goal of improving the intelligence level of the PCS is to make it into an intelligent autonomous control system. This system contains three subsystems, intelligent operation optimization, high-performance intelligent control, and operation condition identification and self-optimization control, as shown in Fig. 6. The intelligent autonomous control system of industrial processes has the following five major functions. ① IntelliSense to detect any changes in production condition. ② Optimizing the operational indices by confirming the set points of the control system adaptively. ③ An intelligent control system with high dynamic performance to track the changes in the set points of the tracking control system and control the actual operational indices within their target ranges. ④ Real-time remote and mobile monitoring and prediction of abnormal conditions, and self-optimization control to eliminate abnormal conditions and ensure system security and optimal operation. ⑤ Cooperating with the intelligent autonomous control systems of other industrial processes to form the global production process and realize global optimization of the production process [12].

3.2.3 Prospective function of the process optimization system

To realize optimal control of the whole production process, we need to optimize the production process parameters. As shown in Fig. 7, the process parameters are determined by process researchers based on their knowledge and experience and through repeated tests of actual production processes. The aim of improving the intelligence level of process parameter research is to develop a process intelligence optimization system that has the following three functions. ① Virtualization of production processes. ② Visualization of the interactions between material flow, energy flow, and information flow in the production process. ③ Optimal processing parameters based on requirements, with the optimum parameters determined by process experts.

4 Key technologies and challenging scientific problems

Enterprise operation and production management with de-

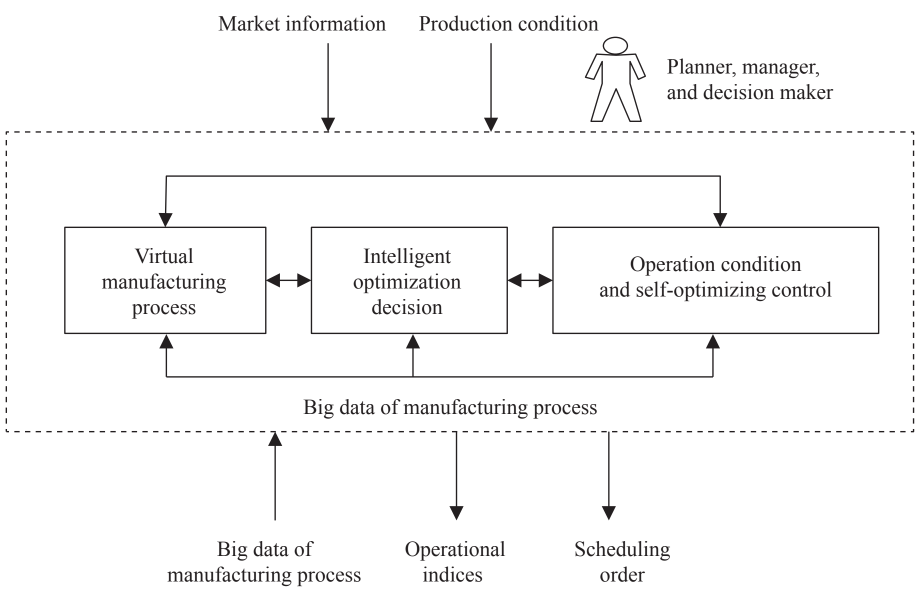

Fig. 5. Intelligent optimization decision system for human–machine cooperation.

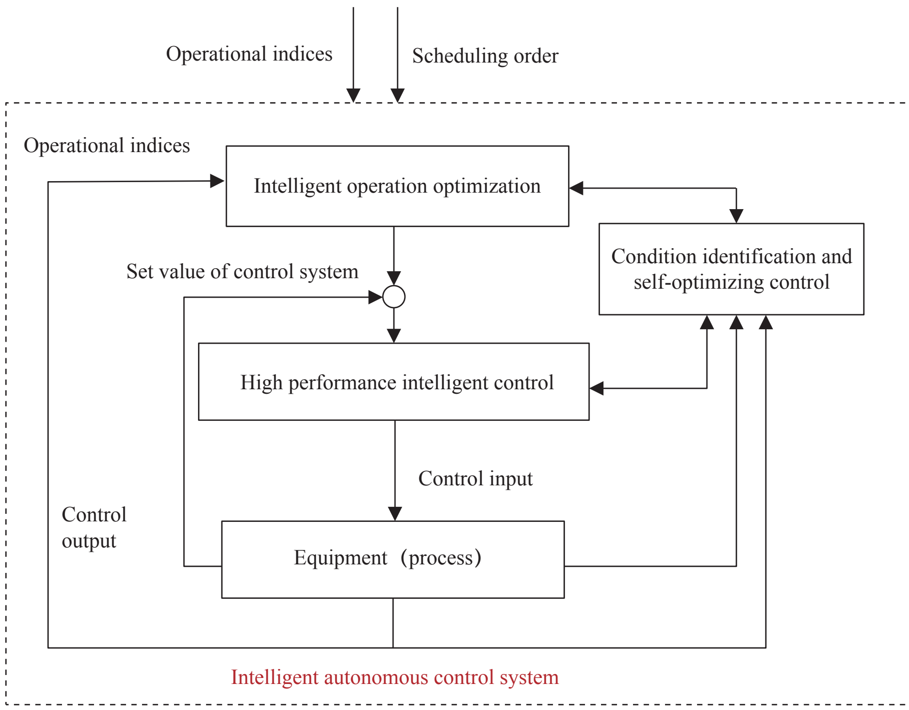

Fig. 6. Industrial process intelligent autonomous control system.

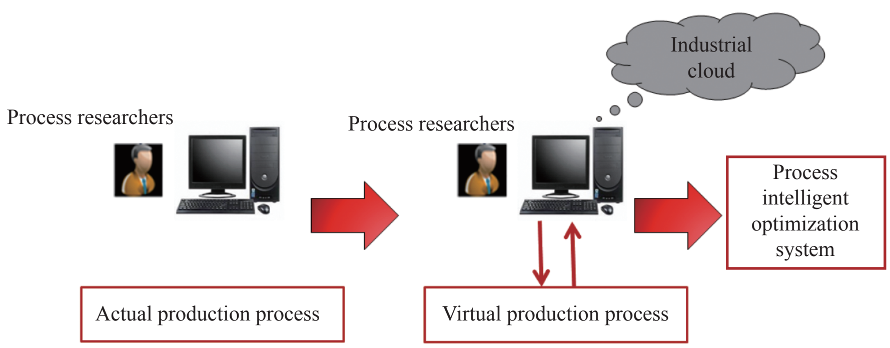

Fig. 7. Process optimization system.

cision making is a complicated integration of three elements, human, machine, and plant, where humans participate in the physical information system at different levels of the hierarchy. The complex industrial process control, operation monitoring and management of the process, analyses of the enterprise operation management and production management, and the decision of optimal process parameters still rely on the experience and knowledge of the knowledge workers. In this context, knowledge workers play a key role in the management and decision making of business operations and production processes. As the Research Report of McKinsey Global Institute has shown, the automation of knowledge work is one of 12 subversive technologies proposed to drive the future global economy [13]. Big data, which have emerged in industries as a large volume of data, can now be produced through complex industrial process control, operation monitoring, and management of the entire process; the management and decision making of enterprise operation; and process research experiments. Industrial big data can be characterized by large data capacity, high sampling rate, and long sampling time (historical, normal, failure, and real time), with many data types such as process variables (control variables, controlled variables), sound and image, management, and operational indices data. The emergence of industrial big data transfers the focus of research to the modeling, operation control, and optimal decision making of business and production processes from the past hypothesis-driven to data-driven methods. Data-based modeling, control, and optimal decision making have become a new hot research topic in automation science and technology [14]. The big data application technology and AI-driven work-based knowledge automation open up a new path for research into the intelligent optimization of the production process and overall intelligent optimization control of the whole process.

For process industry optimization and the overall intelligence optimization of the whole production process, the industrial big data, AI-driven knowledge work automation, communication and computer technology, and physical resources of the process industry need to be closely integrated and coordinated. Also, the following four key generic technologies need to be developed.

(1) An intelligent optimization control technology for industrial processes with comprehensive complexity to realize the whole intelligent cooperative optimization control process and gain optimal control of the global production indices. Besides, the intelligent autonomous control system of industrial process needs to be further developed.

(2) The technology for intelligent modeling, dynamic performance analysis, prediction of key process parameters and production indices, and multi-objective dynamic optimization-based decision making as well as development of an intelligence optimization decision system.

(3) The technology to control the perception and cognition of the big data-driven production processes and develop an operation condition recognition and self-optimization control system.

(4) The technology to control the dynamic intelligence modeling, simulation, and visualization of the interaction of information flow, material flow, and energy flow in the production process of big data- and knowledge-driven production processes, and develop a virtual manufacturing system for the process industry in terms of control, decision making, and process experiment.

To achieve these key technologies, we need to address the challenging scientific problems involving automation science and technology, communication and computer science, and technology and data science.

The scientific challenges to automation science and technology are ① big data-driven intelligent modeling and visualization for complex industrial processes, ② the theory and technology of intelligence optimization control system for industrial processes, and ③ big data- and knowledge-driven multi-objective dynamic intelligence optimization decision-making technology in production operation and management as well as operation and management of industrial processes.

The scientific challenges to computer and communication science and technology are ① industrial equipment-embedded computer control system based on mobile Internet, ② new-generation networked intelligence management and control system supporting big data and knowledge automation, ③ intelligence perception and cognition technology under complex industrial environment, and ④ software platform for intelligence optimization of production processes as well as control of the whole production process.

The scientific challenges to data science are ① how to explore and retrieve useful data from low-value density big data, ② how to deal with unstructured information such as data, text, and image, and ③ how to build a complex dynamic system model based on correlation relationship.

5 Suggestions on development of smart optimal manufacturing for process industries

In order to achieve smart optimal manufacturing for process industries as soon as possible and transform China from a process manufacturer of quantity to one of quality, we offer the following suggestions on the national funding mechanisms and related policies.

5.1 Highlight the strategic position of process industries and enhance the innovation capability of process industry enterprises.

For the formulation of policies and establishment of national development strategies, China needs to establish a strategic position and role for the process industry in its economic development. The process industry in China is developing fast, but it still mainly uses cheap labor and capacity scale to reduce the production cost. In terms of long-term development, the country needs to rely on connotation development to improve innovation and promote economic growth. It should also increase R&D investment and establish a strong R&D and service system and speed up special action programs on smart optimal manufacturing for process industries, construct enterprise-leading industrial technology R&D systems, and promote the collaborative innovation of Government-Industry-University-Research, and thus improve the original innovation capacity of enterprises.

5.2 Jointly carry out strategic planning and top-level design of smart optimal manufacturing for process industries under the consolidated association of universities, R&D institutions, and enterprises.

China needs to set up a strategic research committee composed of experts from all relevant sectors of the country who can effectively leverage the field knowledge of experts under the relevant state departments, and discuss the characteristics, status, and problems of its process industry. Specifically, this committee should locate the contents and challenges arising from the in-depth integration of informationization and industrialization for intelligent manufacturing; focus on R&D ideas, development goals, and key tasks; and clarify the key engineering science and technology problems, key technology, and technical roadmap. In conclusion, the committee is responsible for providing policies and suggestions for implementation and popularization of the in-depth integration of informationization and industrialization in the process industry.

5.3 Accelerate fundamental research and studies on cutting-edge technologies synchronously, make an integrated arrangement of the "National Key Research and Development Programs" supported by MoST, where the "integration of informationization and industrialization in-depth special action plan" supported by MIIT and other related major projects would move forward.

Making use of its superior socialist system, China needs to focus on solving the key engineering and technology problems arising from smart optimal manufacturing for process industries based on the integration of informationization and industrialization, and coordinate the various national research initiatives. Furthermore, the overall investments and subsides for all the projects, ranging from basic science and cutting-edge research, technology research, and product development, to popularization and application, should be arranged overall.

For this, China needs to establish the NSFC-MIIT joint funding scheme to jointly support the basic science and cutting-edge research in smart manufacturing demonstration projects of the process industry.

Furthermore, the country needs to set up major national science and technology projects and national key research and development programs specialized in smart optimal manufacturing for process industries.

The NSFC also needs to initiate major research plans, major projects, and key project groups related to smart optimal manufacturing for process industries.

5.4 Conduct in-depth integration of informationization and industrialization hierarchically, and promote smart optimal manufacturing for process industries.

In this context, leading enterprises related to the in-depth integration of informationization and industrialization need to be chosen for conducting demonstration projects. Stable joint R&D and engineering teams could be formed by associating with enterprises, state key laboratories, and national engineering research centers. Mechanism innovation can be utilized to build up a world-class enterprise by providing the joint team with consistent support.

Furthermore, industry-oriented demonstration projects related to the in-depth integration of informationization and industrialization can be set up. New information technologies (such as big data, cloud computing, industrial Internet, and mobile computing) can be facilitated to build an innovation service platform for the in-depth integration of informationization and industrialization along with an enterprise production management information service platform for different industries such as cloud ERP and cloud MES.

Also, demonstration projects can be implemented to improve the intelligence level of the information system developed for process enterprises. Particular attention should be given to the major production facilities for key production processes, especially those related to high energy consumption equipment. Specifically, the control system should realize intelligence optimization and show improvement in process information collection. The PCS needs to have advanced functionalities such as fault diagnosis and self-recovery as well as optimal control instruction configuration.

5.5 Further improve the sustainable vocational education model and specialty-cultivating pattern so as to build up strong teams of professional technology and R&D talents in the field of smart optimal manufacturing for process industries.

For this, China needs to improve its talent recruitment, cultivation, use, evaluation, and incentive and security policies; optimize the policy circumstances for talent recruitment and cultivation; and train and develop engineering and R&D talent mainly oriented toward industrial innovation requirements. It also needs to improve the employees' occupation accomplishment and build up professional technology and R&D talent teams in the field of smart optimal manufacturing for process industries.

References

[1] Smart Manufacturing Leadship Coalition. Implementing 21st century smart manufacturing [R]. Washington DC: Smart Manufacturing Leadship Coalition, 2011.

[2] Federal Ministry of Education and Research–BMBF. Grasp the future of German manufacturing industry and to implement the strategy of "industrial 4.0" [R]. Bonn: Federal Ministry of Education and Research–BMBF, 2013. Chinese.

[3] Gil Y, Greaves M, Hendler J, et al. Amplify scientific discovery with artificial intelligence [J]. Science, 2014, 346: 171–172.

[4] Chinese Academy of Engineering, National Natural Science Foundation. Research on development strategy of big data and knowledge automation for manufacturing process [R]. Beijing: Chinese Academy of Engineering, National Natural Science Foundation, 2016. Chinese.

[5] Chai T Y. Challenges of optimal control for plant-wide production processes in terms of control and optimization theories [J]. Acta Automatica Sinica, 2009, 35(6): 641–649. Chinese.

[6] Chai T Y, Jin Y H, Ren D X, et al. Contemporary integrated manufacturing system based on three-layer structure in process industry [J]. Control Engineering of China, 2002, 9(3): 1–6. Chinese.

[7] Chai T Y. Research status and development direction of the industry process control system [J]. Scientia Sinica (Informationis), 2016, 46(8): 1003–1015. Chinese.

[8] Executive Office of the President. Artificial intelligence, automation and the economy [R]. Washington DC: Executive Office of the President, 2016.

[9] Executive Office of the President, National Science and Technology Council, Committee on Technology. Preparing for the future of

artificial intelligence [R]. Washington DC: Executive Office of the President, National Science and Technology Council, Committee on Technology, 2016.

[10] Chai T Y. Challenges for artificial intelligence of manufacturing process intelligentize [J]. Science Fundation of China, 2018 (3): 251–256. Chinese.

[11] Chai T Y, Qin S J, Wang H. Optimal operational control for complex industrial processes [J]. Annual Reviews in Control, 2014, 38(1): 81–92.

[12] Chai T Y, Ding J L, Yu G, et al. Integrated optimization for the automation systems of mineral processing [J]. IEEE Transactions on Automation Science and Engineering, 2014, 11(4): 965–982.

[13] McKinsey Global Institute. Disruptive technologies: Advances that will transform life, business, and the global economy [R]. Chicago: McKinsey Global Institute, 2013.

[14] Lamnabhi-Lagarrigue F, Annaswamy A, Engell S, et al. Systems & control for the future of humanity, research agenda: Current and future roles, impact and grand challenges [J]. Annual Reviews in Control, 2017, 43: 1–64.