Theoretical Construction and Development Trends of Intelligent Manufacturing Systems in the Industry 4.0 Environment

Senxu Zhang
Zhengzhou University of Aeronautics, Zhengzhou, Henan, China

Abstract: With the global manufacturing industry entering the intelligent and digital era of Industry 4.0, the theoretical construction and development trends of intelligent manufacturing systems have become the focus of attention in academia and industry. This study aims to systematically expound the theoretical framework of intelligent manufacturing systems in the context of Industry 4.0 and predict their future development directions. Through literature review and theoretical analysis, this research explores the definition, core elements, functional requirements, and technological systems of intelligent manufacturing systems. Based on this, a multi-level theoretical model is constructed, which clarifies the intrinsic logic and interaction mechanisms of intelligent manufacturing systems in perception, analysis, decision-making, and execution. This study further discusses the challenges faced by intelligent manufacturing systems, including technological integration, security, standardization, and talent requirements, and proposes corresponding strategies and recommendations. In the conclusion section, this paper predicts the development trends of intelligent manufacturing systems, including higher levels of automation and intelligence, as well as the trends of technological integration, service orientation, and ecological development.

Keywords: Intelligent Manufacturing Systems; Industry 4.0; Theoretical Construction; Development Trends; Technological Integration

1.1. Introduction

1.1 Research Background and Significance

In the second decade of the 21st century, the pulse of global manufacturing is beating with an unprecedented transformation, driven by the wave of the information technology revolution. the concept of Industry 4.0, like the first ray of sunshine in the morning, illuminates the future of the manufacturing industry, which symbolizes the gorgeous turn of the manufacturing industry from the automation of machinery to the intelligence of wisdom, boundless networking, and deep service. the core of this transformation is the construction and development of intelligent manufacturing systems, which are not only the enhancement of manufacturing efficiency and quality, but also the forging of national competitiveness and sustainable development capabilities. [1-7]

Intelligent manufacturing system, like a craftsman proficient in modern technology, skillfully integrates advanced information technology, Internet of Things, big data analysis, artificial intelligence and other elements together, weaving into an intelligent network covering the whole process of production. This network not only gives the production process the light of wisdom, making it intelligent, flexible and adaptive, but also like an agile dancer, flexibly turns around on the stage of the market, which greatly improves the response speed and adaptability of the manufacturing industry to market changes. [6-10]

Therefore, in-depth study of the theoretical construction and development trend of intelligent manufacturing systems under the environment of Industry 4.0 is like exploring a treasure mountain with infinite possibilities. This is not only the compass for the transformation and upgrading of the manufacturing industry, but also an important magic weapon to enhance industrial competitiveness. It not only has profound theoretical significance, providing theoretical support for the future development of the manufacturing industry, but also has urgent practical significance, providing solutions for the practical challenges of the manufacturing

industry. In this era of change, the research and development of intelligent manufacturing systems is undoubtedly the key to promoting manufacturing to a more brilliant future.

1.2 Research Objectives

This study aims to systematically discuss the theoretical framework of intelligent manufacturing system under the background of Industry 4.0, analyze its core elements, functional requirements and technical system, and predict its future development direction. Through theoretical construction, this study is expected to provide theoretical support for the practical application of intelligent manufacturing systems, and provide references for relevant policy formulation and industrial development.

2. Overview of Industry 4.0 and Intelligent Manufacturing Systems

2.1 Definition and features of Industry 4.0

Industry 4.0, it is not only a term, but also a beacon that leads manufacturing into a new era. the concept was first proposed by the German government in 2011, with the aim of using digitalization and automation technology to promote the fundamental transformation and upgrading of the manufacturing industry. Industry 4.0 represents the fourth industrial revolution from the revolution of steam engines, electricity, and information technology to comprehensive intelligence, and it marks a new stage in the development of manufacturing. [10-13]

The core characteristics of Industry 4.0 can be summarized in five aspects: highly automated, networked, intelligent, service-oriented and sustainable.

High degree of automation: In the environment of Industry 4.0, production processes and operations achieve a high degree of automation. This automation is not limited to the physical production process, but also includes production planning, logistics and services. Through advanced control systems and robotics, factories are able to achieve more efficient and precise production with less human intervention.

Networking: This is one of the core features of Industry 4.0, which refers to the connection of production equipment, products and systems through the Internet, especially the industrial Internet, to achieve the immediate circulation and sharing of information. This connectivity is not limited to the factory, but also includes the upstream and downstream of the supply chain and the client, achieving information transparency and collaborative work across the entire industrial chain.

Intelligence: Intelligence is through the integration of artificial intelligence, big data analysis, machine learning and other technologies to achieve self-learning, self-optimization and self-adjustment of the production process. This means that production equipment and systems can automatically make decisions and optimizations based on changes in production data and the external environment, improving production efficiency and quality.

Service: Industry 4.0 emphasizes the integration of manufacturing and service industries to enhance the competitiveness of products by providing value-added services. This service is not only reflected in the after-sales service, but also includes the design, manufacturing, use and recycling of the entire product life cycle, providing customers with a full range of personalized solutions.

Sustainability: Sustainability is concerned with the efficient use of resources and energy in the production process, reducing waste and emissions, and achieving harmonious economic, social and environmental development. Through real-time data analysis and intelligent management, factories are able to optimize energy use and reduce production costs while reducing their environmental impact.

For example, according to relevant research [1], in the environment of Industry 4.0, factories can carry out real-time data analysis by realizing the interconnection of equipment and systems, which can not only optimize the production process and improve production efficiency, but also significantly improve the efficiency of energy use. Through intelligent data analysis, the factory can precisely control the energy consumption in the production process, achieve the optimal distribution and use of energy, so as to achieve the purpose of energy conservation and emission reduction.

The implementation of Industry 4.0 is undoubtedly a profound revolution to the traditional manufacturing model. Through digital and intelligent means, it provides a new

direction for the future development of the manufacturing industry, which not only improves production efficiency and economic benefits, but also promotes the optimization and upgrading of the industrial structure, and opens up a new road for achieving sustainable development.

2.2 Concept and Connotation of Intelligent Manufacturing System

Intelligent manufacturing system, the concept came into being in the wave of industry 4.0, it is like a precision clock, advanced information technology, automation technology, artificial intelligence and other elements cleverly integrated together to build a highly intelligent, networked, automated production system. This system is not only the accumulation of technology, but also an innovation of production mode, which covers the all-round change from intelligent design to intelligent production, and then to intelligent service.

In the framework of intelligent manufacturing system, intelligent design refers to the use of advanced computer-aided design (CAD), simulation, virtual reality and other technologies to achieve rapid iteration and optimization of product design. Designers can use these tools to test and adjust products in a virtual environment, greatly reducing the time from design to market, while also improving the accuracy and innovation of the design.

Intelligent production is the core of intelligent manufacturing system, it through the integration of automated production lines, robotics, the Internet of Things (IoT), etc., to achieve a high degree of automation and intelligence in the production process. In this process, the production equipment can exchange data in real time and automatically adjust the production parameters to adapt to the changing production needs. This intelligent production method not only improves production efficiency, but also reduces production costs and improves product quality.

Intelligent service is an important part of intelligent manufacturing system, which emphasizes providing personalized and customized services to customers through data analysis and artificial intelligence technology. After product sales, by collecting and analyzing user usage data, enterprises can provide more accurate maintenance, upgrade and optimization services, enhance user experience and enhance customer loyalty.

The connotation of intelligent manufacturing system lies in its highly integrated and intelligent. In this system, all production resources, including manpower, equipment, materials, etc., can be optimized through intelligent algorithms to achieve the maximum utilization of resources. the production process is no longer a single, linear flow, but a dynamic, adaptive network capable of intelligent control and adjustment based on real-time data. This comprehensive monitoring and intelligent decision-making enables the production system to quickly respond to market changes, flexibly adjust production strategies, and achieve truly intelligent manufacturing.

In short, intelligent manufacturing system is the core competitiveness of the manufacturing industry in the era of Industry 4.0, it promotes the transformation of production mode through technological innovation and application, and provides a strong support for the transformation and upgrading of the manufacturing industry. With the continuous advancement of technology and the deepening of applications, intelligent manufacturing systems will continue to evolve, leading the manufacturing industry to a more intelligent, efficient and sustainable future.

2.3 The impact of Industry 4.0 on Intelligent Manufacturing Systems

The development of Industry 4.0 has had a profound impact on intelligent manufacturing systems. First of all, Industry 4.0 has promoted the technological innovation of intelligent manufacturing systems, such as the application of technologies such as the Internet of Things, cloud computing, and big data, so that intelligent manufacturing systems can achieve more efficient data processing and analysis. Secondly, Industry 4.0 promotes the integrated development of intelligent manufacturing systems, and through system integration, intelligent manufacturing systems can achieve cross-departmental and cross-enterprise collaborative work. Finally, Industry 4.0 emphasizes the service-oriented transformation of intelligent manufacturing systems, that is, from traditional manufacturing to providing personalized and customized services. For example, the research of [2] shows that intelligent manufacturing systems in the

environment of Industry 4.0 can accurately predict customer needs through data analysis, so as to provide more personalized products and services.

3. Theoretical Construction of Intelligent Manufacturing System

3.1 Core elements of Intelligent Manufacturing System

Intelligent manufacturing system is the implementation carrier of the core of Industry 4.0, which integrates the main characteristics of Cyber-Physical Systems (CPS). the core elements of intelligent manufacturing systems not only cover the whole process from physical equipment to information processing, but also include human participation and the application of emerging technologies. These core elements are demonstrated in detail below.

(1) Smart devices

Intelligent equipment is the basic unit to realize physical operation in intelligent manufacturing system. It has certain data processing and autonomous decision-making ability through the application of embedded system. For example, intelligent robots can not only automatically complete complex tasks such as handling and assembly according to preset programs, but also realize environment recognition and adaptation through sensing technologies such as machine vision, and even learn and optimize the production process [1]. These devices are interconnected through the Industrial Internet of Things (IIoT) to support remote monitoring and control, greatly improving the flexibility and efficiency of production.

(2) Information system

Information systems such as ERP, MES and PLM systems are the brains of intelligent manufacturing, which is responsible for coordinating and optimizing resource allocation and business processes inside and outside the enterprise. ERP system can realize the comprehensive integration of enterprise resource planning, while MES system is responsible for the management of manufacturing execution process, and PLM system manages all stages of the product life cycle. These systems ensure the smooth progress and continuous optimization of production activities through real-time data exchange and processing [2].

(3) Network communication

Intelligent manufacturing system relies on advanced network communication technology to ensure real-time data transmission and instant communication between devices. Today, industrial Ethernet and 5G communication technologies are becoming the new standard for industrial communications, supporting higher data transfer rates and lower latency, providing the infrastructure for intelligent manufacturing. the application of these technologies not only makes remote monitoring and control possible, but also provides a guarantee for real-time analysis and processing of large amounts of data [3].

(4) Data analysis

In intelligent manufacturing systems, data analysis is the key to giving the system intelligence. Through the acquisition of equipment and sensors, the system is able to obtain a large amount of production data, and using cloud computing and big data analysis technology, valuable insights can be extracted from it to guide the optimization and improvement of production. Through machine learning algorithms, the system can also independently discover the causes of low production efficiency and automatically adjust production strategies to improve the overall efficiency and respond to market changes [4].

(5) Artificial intelligence

With the development of artificial intelligence technology, intelligent manufacturing systems are increasingly integrating machine learning, deep learning and other algorithms, which can learn based on a large amount of data, so that the system has intelligent behaviors such as predicting faults, optimizing production processes, and adaptive adjustment of production plans. For example, in the production line, through real-time data analysis, intelligent manufacturing systems can predict the maintenance time of equipment, reducing the risk of production disruptions [5].

3.2 Analysis of Functional Requirements of Intelligent Manufacturing System

Intelligent manufacturing system is the core component of Industry 4.0, and the analysis of its functional requirements is the basis for achieving high-quality development of manufacturing industry. Intelligent manufacturing systems not only need to realize the automation and intelligence of the

production process, but also need to ensure that they can flexibly respond to market changes, achieve efficient allocation of resources, ensure the reliability and safety of the production process, and provide personalized and customized services.

Production automation and intelligence are the basis of intelligent manufacturing system. Through the introduction of advanced automation equipment and robotics, coupled with efficient production control systems and intelligent decision support systems, intelligent manufacturing systems can effectively improve production efficiency and product quality. In addition, by using artificial intelligence algorithms for data analysis and learning, the system can realize self-optimization and further improve the flexibility and intelligence of production [1].

In the intelligent manufacturing system, how to optimize the allocation of production resources is another important demand. By using advanced algorithms to dynamically optimize the allocation of production resources, it can not only improve the utilization rate of resources, but also reduce the production cost. For example, particle swarm optimization (PSO) algorithm and genetic algorithm (GA) are used to optimize the equipment layout, raw material supply and human resource allocation of the production line, which can achieve the double improvement of production efficiency and resource utilization [2].

In order to ensure that the production process of the intelligent manufacturing system can be carried out smoothly and efficiently, it is essential to realize the real-time monitoring and feedback of the production process. By deploying sensors and acquisition devices, the system can collect real-time production data, such as equipment operating status, production environmental conditions, and product quality information. By analyzing this information, the system can find and solve the problems in the production process in time to ensure the continuity of production and product quality [3].

With the increasing diversification of market demands, intelligent manufacturing systems also need to provide personalized and customized services. By integrating design and manufacturing systems, combined with customer relationship management (CRM) systems, intelligent manufacturing systems can quickly design and produce products that meet the needs of customers according to their specific needs. In addition, the use of big data analysis and artificial intelligence technology can further tap customer needs and improve the personalized level of product design and service [4].

3.3 Construction of technical system of intelligent manufacturing system

The technical system construction of intelligent manufacturing system is the key to realize its functional requirements. This system needs to integrate technology from multiple fields such as information technology, automation technology, artificial intelligence technology and Internet of Things technology to build an efficient, flexible and intelligent manufacturing system.

Information technology is one of the basic technologies of intelligent manufacturing system. By applying technologies such as big data analysis, cloud computing, Internet of Things and edge computing, intelligent manufacturing systems can realize real-time collection, storage, analysis and processing of production data to support intelligent decision-making and management of production processes.

Automation technology is the key to realize production automation. Through the introduction of high-precision automation equipment and robots, as well as efficient production control systems, production efficiency and product quality can be significantly improved, while reducing production costs.

Artificial intelligence technology, especially the application of machine learning and deep learning technology, provides the possibility for self-learning and self-optimization of intelligent manufacturing systems. Through in-depth analysis and learning of production data, the system can continuously optimize the production process and improve the flexibility and intelligence of production.

The integration of Internet of Things technology can realize the effective connection and management of production resources. By deploying sensors and smart devices to build a highly connected production environment, intelligent manufacturing systems can monitor and manage production resources in real time, improving the efficiency and accuracy of

resource allocation.

3.4 Theoretical model construction of intelligent manufacturing system

The construction of the theoretical model of intelligent manufacturing system is the theoretical basis for realizing its functional requirements and constructing its technical system. This model needs to comprehensively consider the automation and intelligence of the production process, the optimal allocation of resources, real-time monitoring and feedback, and the provision of personalized services, etc., to build a complex system model containing multiple levels and modules.

The theoretical model of intelligent manufacturing system can be divided into multiple levels, including physical layer, control layer, information layer and service layer. the physical layer is responsible for the physical operation and production activities in the production process; the control layer realizes the control of the production process through automation technology and equipment; the information layer uses information technology to collect, analyze and process production data. the service layer provides personalized product design and service.

The theoretical model of intelligent manufacturing system also needs to adopt modular design method. By dividing the system into multiple functional modules, such as production scheduling module, resource management module, quality control module and customer service module, the flexibility and scalability of the system can be improved. Each module is designed and implemented using the most appropriate technology to meet the corresponding functional requirements.

4. Analysis of the Development Trends of Intelligent Manufacturing Systems

Intelligent Manufacturing Systems (IMS) is one of the core technologies in the environment of Industry 4.0. Through highly integrated Cyber-Physical Systems (CPS), Internet of Things (IoT), artificial intelligence (AI) and other advanced technologies, it realizes the optimal allocation of manufacturing resources, improves production efficiency and product quality. Realize the transformation and upgrading of the manufacturing industry [1]. From technology development to system integration, to service, personalization and green sustainable development, intelligent manufacturing systems show a multi-dimensional development trend.

4.1 Technology development trends

The development of intelligent manufacturing technology is the fundamental driving force to promote the transformation and upgrading of the manufacturing industry. Among them, artificial intelligence, big data, cloud computing, Internet of Things and robotics are the most critical technical support [2]. the development of AI provides data analysis, decision support, adaptive control and other capabilities for intelligent manufacturing, and enables equipment to have the ability to learn and optimize independently through machine learning and deep learning technology. the application of the Internet of Things technology realizes the interconnection of equipment and real-time data collection, and provides the data basis for the intelligent production process. Cloud computing provides a powerful data processing capability and resource sharing platform for intelligent manufacturing, and promotes the flexible scheduling and optimal allocation of production resources. the integration and development of these technologies make intelligent manufacturing systems tend to be more intelligent, automated and networked.

4.2 System integration trend

In the environment of Industry 4.0, intelligent manufacturing systems are developing in the direction of more integration. This kind of integration is not only the integration at the technical level, but also the deep integration of multiple dimensions such as process, equipment, personnel and management [3]. Through the realization of CPS, the physical manufacturing system and virtual information system achieve a high degree of synchronization, and through real-time data exchange and analysis, the deep integration of design, production, management and other processes is realized. In addition, system integration is also reflected in the efficient use and optimal allocation of manufacturing resources, through cloud manufacturing, edge computing and other technologies, to achieve the network allocation of productivity resources and services, improve the flexibility

and response speed of the manufacturing system.

4.3 Trends of servitization and personalization

With the increasingly diversified and personalized needs of consumers, intelligent manufacturing systems are developing in the direction of service and individuation. On the one hand, through big data analysis and artificial intelligence technology, intelligent manufacturing system can accurately grasp market demand and user preferences, and realize rapid customization and personalized production of products [4]. On the other hand, the servitization of intelligent manufacturing refers to the transformation of manufacturing capabilities into service capabilities through intelligent technology, such as remote maintenance, cloud services, etc., which not only improves the added value of manufacturing, but also promotes the extension and upgrading of the industrial chain.

4.4 Greening and sustainable development trend

On a global scale, greening and sustainable development have become the inevitable trend of future development. While promoting the development of manufacturing industry, intelligent manufacturing system also attaches great importance to environmental protection and resource conservation [5]. Through accurate data analysis and intelligent decision-making, intelligent manufacturing can optimize the production process, reduce energy consumption and raw material consumption, and reduce the generation of waste. In addition, intelligent manufacturing also promotes the development of circular economy, through intelligent recycling and reuse technology, improve the utilization efficiency of resources, and achieve a win-win situation between economic development and environmental protection.

5. Challenges Faced by Intelligent Manufacturing Systems and Countermeasures

With the advancement of Industry 4.0, intelligent manufacturing system (IMS) has become the core of the transformation and upgrading of the manufacturing industry. However, the process is not without obstacles. This section will discuss the challenges faced by intelligent manufacturing systems in technology integration and innovation, security and privacy protection, standardization and interoperability, talent training and knowledge management, and propose corresponding countermeasures.

5.1 Technology integration and innovation challenges

The core of intelligent manufacturing system lies in the integration and innovation of technology. However, this process faces many challenges. First, the integration between different technologies requires interdisciplinary knowledge and skills, which puts higher demands on R&D personnel. Second, the rapid iteration of technology makes it difficult for companies to keep up with the pace of innovation, especially when capital and resources are limited.

Coping strategies: To overcome these challenges, companies need to build interdisciplinary research and development teams and encourage collaboration among experts in different fields. At the same time, enterprises should increase investment in research and development, and accelerate the pace of technological innovation by establishing innovation centers and cooperating with universities and research institutions. In addition, enterprises can ease the financial pressure by introducing venture capital and government subsidies.

5.2 Security and Privacy protection challenges

With the development of intelligent manufacturing systems, data security and privacy protection have become an increasingly serious problem. On the one hand, intelligent manufacturing systems rely on massive data exchange, which makes the system vulnerable to cyber attacks. On the other hand, sensitive personal and corporate information may be leaked during data transmission and storage.

Countermeasures: In order to ensure the security of the system, enterprises need to adopt advanced network security technologies, such as encrypted communication, intrusion detection system and firewall. At the same time, enterprises should establish strict data management policies to ensure the legal use of data and privacy protection. In addition, the

government should formulate relevant laws and regulations to strengthen the supervision of data security and privacy protection.

5.3 Standardization and interoperability challenges

The standardization and interoperability of intelligent manufacturing systems are the key to realize seamless connection between systems. However, due to the different technical standards adopted by different manufacturers, interoperability between systems is limited. This not only affects the efficiency of the system, but also increases the cost of the enterprise.

Response: To address this problem, industry organizations and governments should promote the development of uniform technical standards to promote interoperability between different systems. At the same time, enterprises should actively participate in the process of standardization, and jointly promote the development of the industry through cooperation and exchange. In addition, enterprises can improve the flexibility and scalability of their systems by adopting open architecture and modular design.

5.4 Talent training and knowledge management challenges

The development of intelligent manufacturing system puts forward new requirements for talents. Traditional manufacturing talents often lack the knowledge and skills of digitalization and intelligence. In addition, with the rapid update of knowledge, enterprises are faced with the challenge of knowledge management.

Coping strategies: In order to cultivate talents who adapt to intelligent manufacturing systems, enterprises and educational institutions should strengthen cooperation and provide targeted training and education programs. At the same time, enterprises should establish an effective knowledge management system and promote the accumulation and dissemination of knowledge through internal training, knowledge sharing platform and incentive mechanism. In addition, companies can quickly enhance the professional capabilities of their teams by bringing in outside experts and consultants.

6. Conclusion

As the core of Industry 4.0, intelligent manufacturing system faces many challenges in its development. Through the efforts of technology integration and innovation, security and privacy protection, standardization and interoperability, as well as talent training and knowledge management, these challenges can be effectively addressed and the healthy development of intelligent manufacturing systems can be promoted. In the future, with the continuous progress of technology and the deepening of applications, intelligent manufacturing systems will play a more important role on a global scale.

Reference

[1] Jiang Dehong. Application research on construction of Nanfang Cement Smart Factory [D]. Shanghai Jiao Tong University, 2016.

[2] Liu Jianxin. Manufacturing unit control system based on the CPS [D]. the design and implementation of Beijing jiaotong university, 2016. the DOI: 10.7666/d. Y. 3124512.

[3] ZHAO Rong. Application Research of Intelligent Manufacturing in Home Appliance Enterprises [D]. Shanghai Jiao Tong University, 2015.

[4] Yang Zhencai. Transformation analysis of precision casting Industry combined with Big Data [C]// China Casting Industry Series Conference (384) -- the 15th China Casting Precision Casting Annual Conference. Hong Kong Association of Chinese Medicine, Educational Research Foundation, 2017.

[5] Fu Jianzhong. the present situation and the tendency of the development of intelligent manufacturing equipment [J]. Mechanical and electrical engineering, 2014, 31(8):4. DOI: CNKI: SUN: JDGC. 0.2014-08-001.

[6] Wei Chang You. Application and development trend of PLC technology in Mechanical Engineering control System in the era of intelligent manufacturing [J]. China Equipment Engineering, 2022(24):219-221.

[7] Fu Jianzhong. Development Status and Trend of Intelligent Manufacturing Equipment [J]. Mechanical and Electrical Engineering, 2014(008):031.

[8] WAN Hao. " Industry 4.0" promotes mechatronics to intelligent technology system [J]. Electronic test, 2019(2):2. DOI:

CNKI: SUN: WDZC. 0.2019-02-053.

[9] TaoFei. 4.0 with the development trend of intelligent manufacturing industrial Jane [J]. Chinese training, 2017(12):36 37. DOI: 10.14149/j. carol carroll nki. Ct. 2017.12.016.

[10] Xi Chongbin. Intelligent manufacturing and intelligent logistics system construction [J]. Journal of logistics technology and applications, 2015(6):41. DOI: CNKI: SUN: WLJY. 0.2015-06-012.

[11] Sheng Li. Industrial age 4.0 a guest, the innovation education in colleges and universities to explore [J]. Journal of party construction and ideological education, the school 2016. DOI: CNKI: SUN: XXDJ. 0.2016-13-026.

[12] KAN Fenglong, Wang Yanchen, Liu Shujuan. Research on Strategies for Accelerating the Development of Intelligent Manufacturing in Shenyang under the background of Industry 4.0 [C]// Proceedings of the 13th Shenyang Science Annual Conference (Economics, Management and Social Sciences). 2016.

[13] Liu Hushen, Li Ke, Wang Heming, et al. 4.0 based on the quality of printed circuit board intelligent defect detection study [J]. Journal of systems engineering and electronics, 2024, 46(5):1682-1690. the DOI: 10.12305/j. i SSN. 1001-506 - x. 2024.05.21.

