Journal of Computing and Electronic Information Management
ISSN: 2413-1660 | Vol. 11, No. 1, 2023

Literature Review on Smart Manufacturing Upgrades for Manufacturing Enterprises

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Abstract: Smart manufacturing is an important way to achieve a strong manufacturing country and a power engine to promote the rapid development of the country's secondary industry economy. As smart manufacturing enters the stage of comprehensive promotion, there is an urgent need to put forward reasonable suggestions for the measurement of capability elements and their evolution. This paper compares the research results about the leap of smart manufacturing hierarchy in recent years, summarizes the issues related to smart manufacturing from the connotation, development paradigm, role mechanism, capability elements and hierarchy, and discusses the future research directions about the leap of smart manufacturing hierarchy.

Keywords: Smart manufacturing; Capability elements; Hierarchy; Development paradigm; Literature review.

1. Introduction

Driven by the wave of Industry 4.0, the world's major developed economies have made important decisions to seize the high position of the manufacturing value chain, focusing on smart manufacturing and using it as the main grip to develop national manufacturing. The U.S. National Advanced Manufacturing Strategic Plan proposes the use of digital manufacturing technologies and the development of data compatibility standards to enable seamless integration of smart manufacturing. Prioritize artificial intelligence technologies in machine learning, data access, confidentiality, encryption, and risk assessment, while using human-centered technologies to facilitate the development of new technologies and standards. Germany's Recommendations for the Implementation of Industry 4.0 Strategy makes detailed guiding recommendations in eight aspects of smart manufacturing: standardization and reference architecture, management of complex systems, infrastructure construction, information security and assurance, organization and design of work, training and career development, regulations, and effective use of resources through the perspectives of technology application, organizational design, and resource orchestration. France's New Industrial France takes digital transformation and upgrading as an important opportunity to shift economic development toward the industrial sector and use emerging digital intelligence technologies to guide the intelligent transformation and upgrading of industrial manufacturing by innovative means. Japan's White Paper on Manufacturing in Japan emphasizes the transition to a super-smart society 5.0 by using the "Connected Industry" strategy as a guide to achieve a high degree of digitalization in manufacturing plants and a high degree of human-machine-object interconnection in order to leapfrog the stage of discontinuous innovation in its industry. In the strategic game of manufacturing competition among manufacturing countries, China stands at the historical intersection of a new round of scientific and technological revolution and industrial change, and in order to break through the problems of poor adaptability of manufacturing supply and market demand, challenges to the stability of the industrial chain supply chain, and tightening of resource and environmental constraints, it is determined to develop smart manufacturing as the main direction, promote industrial technology change and optimization and upgrading, promote the fundamental transformation of the manufacturing industry model and enterprise form, drive the "old" with the "new", improve quality, efficiency and effectiveness, reduce resource and energy consumption, and smooth the industrial chain supply chain.

2. Status of smart manufacturing research

2.1. Data sources and analysis

In 2013, the Ministry of Industry and Information Technology issued a Special action plan (2013-2018) on the issuance of deep integration of information technology and industrialization. Therefore, using 2013 as the starting point, we searched the CSSCI articles on the theme of "smart manufacturing" from 2013 to 2023 through the CNKI database, and retrieved a total of 672 articles, covering 30 categories of topics such as "smart manufacturing", "Industry 4.0", and "transformation and upgrading" and other 30 categories of topics (As shown in Figure 1 and Figure 2). From the trend analysis, the annual trend of this topic from 2013 to 2022 shows an overall increasing trend. 51 articles have been published in 2023 as of July, and it is expected that the number of articles will exceed that of 2022 by the end of the year, which indicates that "smart manufacturing" is still a hot spot for research nowadays, which is closely related to the vigorous promotion of smart manufacturing in China.

By extracting the key words of the articles, we can divide them into 30 categories, among which 190 articles are about "smart manufacturing", mainly about the connotation, development and impact of smart manufacturing on traditional industries; 57 articles are about "manufacturing industry".

There are 57 articles with "manufacturing" as the keyword, because smart manufacturing and traditional manufacturing industries are in an interactive relationship; other topics also involve the relevant technologies used in smart manufacturing, the influencing factors and mechanisms, etc.

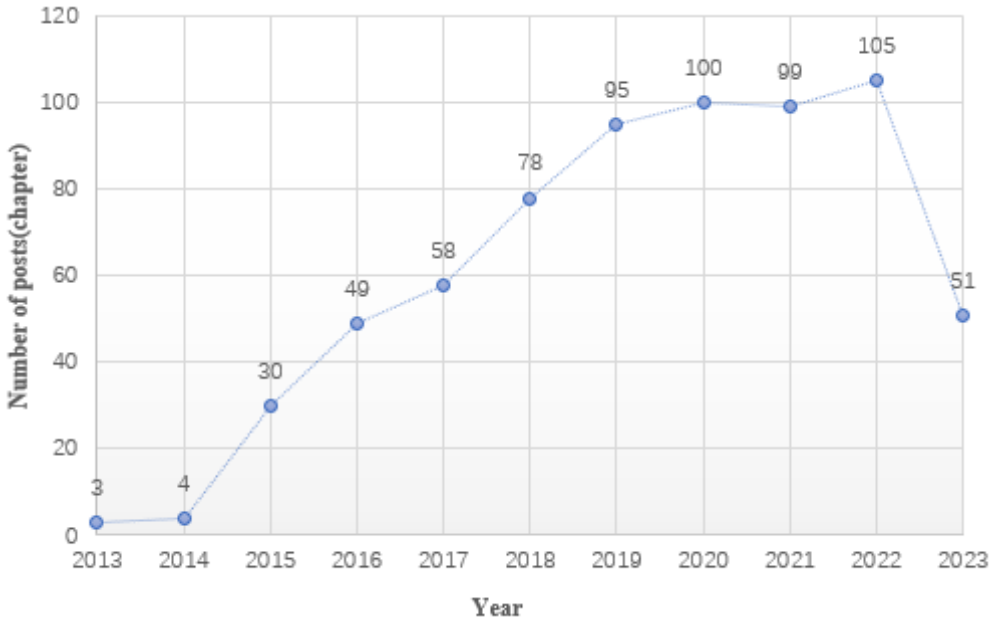


Figure 1. Trends in published articles 2013 - July 2023

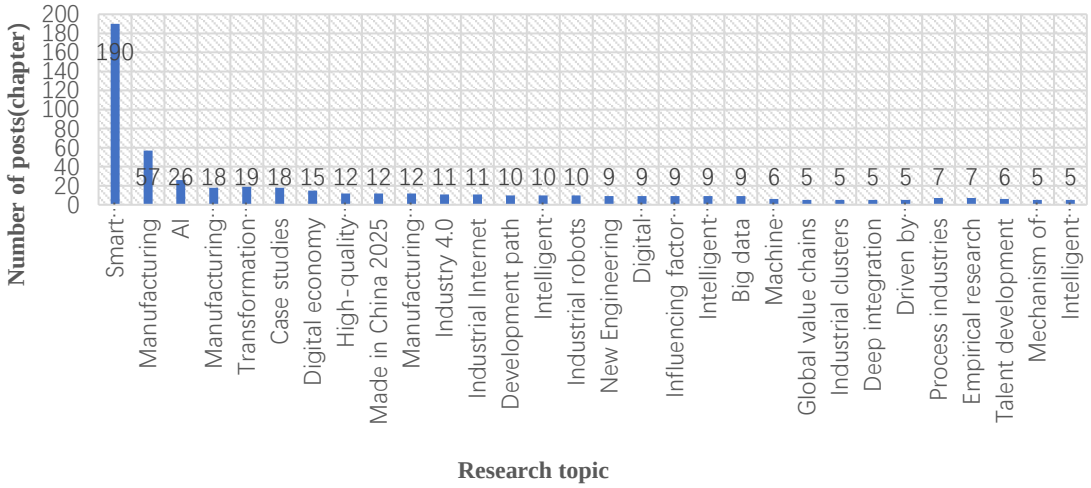


Figure 2. Overview of the topics of published articles

2.2. Smart Manufacturing Connotation

With the increasing maturity of algorithms and computer technology, the global manufacturing industry is converging on smart manufacturing to promote the rapid development of secondary industries in their countries. Enterprises are strongly willing to "increase quality and reduce costs", and highly integrated and personalized production has become the mainstream development direction of enterprise manufacturing [1-2]. Big Data, IoT, 5G, AI, Digital Twin and other new generation of information technology provide strong support for the Industry 4.0 revolution, and the production mode of manufacturing industry tends to be multi-variety, small batch, flexible automation and smart[3-4]. More diversified user needs, and the increase in product accuracy and quality requirements, feedback to the production process is manifested in the reliance on knowledge and technology greatly exceeds other factors of production, which makes technology-intensive has become the mainstream trend of modern manufacturing, smart manufacturing was born[5-6]. Smart manufacturing is an evolving overall concept. In a broad sense, smart manufacturing is the deep integration of new generation information technology and advanced manufacturing technology throughout the whole life cycle of products, manufacturing and services and the optimization and integration of the corresponding systems to realize the digitization, networking and intelligence of manufacturing and continuously improve the quality, efficiency and service level of enterprises, and promote the means of innovative, green, coordinated, open and shared development of manufacturing industry[7]. Specifically, smart manufacturing refers to the whole life cycle of product manufacturing process, the use of a new generation of automation technology, sensing technology, network technology, anthropomorphic intelligence technology and other intelligent means to achieve manufacturing production equipment and manufacturing process perception, interaction, implementation of the driving force[8-9]. In general, whether in a broad sense or in a specific concept, smart manufacturing is a transformation process that relies on emerging technologies and advanced equipment and is based on the strategic adjustment of the organization to intelligently empower the overall industrial chain to achieve a high degree of intelligence in the industrial chain.

2.3. Smart Manufacturing Development Paradigm

The basic development paradigm of smart manufacturing is similar, and the current mainstream studies all agree that the development of smart manufacturing will go through digital manufacturing, networked manufacturing, smart manufacturing (new generation of smart manufacturing)[7,10]. Digital manufacturing is the first stage in the process of upgrading smart manufacturing, and also throughout the whole process of upgrading smart manufacturing[7]. Its general characteristics are summarized in the digitization of production factors, which is the digital description, analysis, decision making and control of product information, process information and resource information by digital manufacturing in the context of the integration of digital technology and manufacturing technology. In this way, digital manufacturing significantly reduces the time required to design and manufacture products to meet specific customer requirements[11-13].Based on the digital manufacturing stage of digital production factors, the use of network interconnection technology combined with manufacturing technology to achieve close connection of people, processes, data and things in the production and manufacturing activities is called the networked manufacturing stage[14-15]. From the perspective of enterprises, the information data transmission path, rate and stability of enterprises in the networked manufacturing stage are greatly improved, their internal and external integration capabilities are enhanced, the degree of collaboration is increased, and the sharing and integration of production factors also have obvious progress, which makes the overall interaction and synergy of the enterprise chain has a significant increase, whether from the product level of design and development, horizontal and vertical integration of the manufacturing process, or from the service level of the interaction between enterprises and users through the network platform, the networked manufacturing stage is an essential change compared to the digital stage[16-17]. Based on advanced manufacturing technology, with the support of a new generation of emerging technologies, including digitalization and networking and integration of cloud computing, big data, Internet of Things and artificial intelligence, highly smart manufacturing activities with self-awareness, self-decision, self-execution and self-optimization are the new form of smart manufacturing, and also the highest degree that manufacturing industry can reach so far, which mainly involves big data intelligence, human-machine hybrid enhanced intelligence, crowd intelligence and cross-media intelligence[18-20]. Smart manufacturing can reshape the whole life cycle of products, so that each link of the manufacturing chain can complete its own activities with the highest efficiency and collaboration with other links, while constantly deriving new products, new industries and new models. Digitalization, networking and smart manufacturing are the basic development paradigms for the transformation and upgrading of smart manufacturing in the manufacturing industry and Enterprises, and the three paradigms are synergistic development methods.

2.4. Mechanism of the role of smart manufacturing

The impact of smart manufacturing on the manufacturing value chain and industry chain is huge, and it is important for enterprises to transform and upgrade their production systems through the implementation of smart manufacturing to improve product quality, reduce production and operation costs, and shrink the time to market in order to cope with the fierce market competition and diversified market demands[21-22]. Research on the specific impact of smart manufacturing on the manufacturing industry is mostly discussed from the perspective of enterprises. From the perspective of "input-performance", the increase in R&D investment and knowledge absorption capacity of enterprises can effectively execute the "search-selection" cycle of problem solving in organizational units, which feeds back to the smart manufacturing itself, that is, the improvement of information processing technology capability due to technological innovation. The improvement of information processing technology capability, which has an obvious positive effect on enterprise performance[23-24]. At the same time, due to the advantages of the unique technology system of smart manufacturing, it can effectively blur the boundaries between the internal organizational structure of enterprises and external enterprises, which makes the access and rate of information, the key factor of enterprise innovation activities, effectively improved, while the big data, cloud computing, machine learning and other technologies in the composition of smart manufacturing technology system further improve the ability of enterprises to analyze and process technology, reduce the uncertainty in the innovation process, thus effectively guaranteeing the stability of innovation[25-27]. Furthermore, smart manufacturing is the most influential part of manufacturing activities for enterprises. The construction of key technologies and the introduction of production equipment make manufacturing activities change. Unlike traditional manufacturing activities, the scope of smart manufacturing involves the whole life cycle of the product, including design, production, logistics, operations, etc., making manufacturing activities more lean, flexible and intelligent. For example, the combination of virtual and real personalized design, personalized product design for customer needs numerical design, short cycle time, real-time dynamic change, which can effectively meet customer needs; processing flexibility, real-time adjustment of the whole process of intelligent processing and online real-time monitoring of production organization personalized network of human-computer interaction intelligent control of reduction, a variety of processing and molding, processing efficiency and quality significantly improved[28-29].

2.5. Enterprise smart manufacturing upgrade

2.5.1. Factors influencing the upgrade of enterprise smart manufacturing

The fundamental responsibility bearer for the development of national and industrial smart manufacturing is manufacturing enterprises. In order to effectively promote the effective upgrading of enterprise smart manufacturing, current research focuses on the analysis of the influencing factors of enterprise smart manufacturing. Some scholars believe that enterprise digitalization, integration and interconnection, technological innovation have a significant role in promoting the transformation and upgrading of traditional manufacturing to smart manufacturing[8]. Digitalization for the development of smart manufacturing to enhance the dynamic perception of enterprises, data elements processing and analysis capabilities, and can reshape industrial processes and decision-making mechanisms, while causing changes to the cost structure of enterprises[30-31];

The integrated interconnection plays an important role in promoting the construction of intelligent collaborative ecology, promoting the effective cycle of enterprise intelligent ecological chain, and promoting the dynamic matching and integration of resources[32]. Technological innovation through technology imitation, digestion and innovation process to develop new technologies or reinvention of existing technologies is the main way for enterprises to provide strong technical support for themselves, which to a certain extent can be separated from the key core components of smart manufacturing equipment dependent on imports, the lack of independent innovation dilemma[33]. The introduction of national policies effectively guides manufacturing enterprises to upgrade smart manufacturing, and the relevant technology research and development policies, technology transformation policies and related supporting policies indicate the focus of resource arrangement and utilization. At the same time, staff knowledge and management ability play a prominent role in the process of smart manufacturing, and the cultivation and construction of "high precision" comprehensive talents is of great significance to the overall construction of smart manufacturing[34-35].

2.5.2. Capability elements and hierarchies of enterprise smart manufacturing upgrade

The transformation and upgrading of traditional manufacturing industry to smart manufacturing will go through three stages of digitalization, networking and intelligence "synergy and integration development". The basis for the division of each stage is determined based on the specific development of the current industry. Further, the three stages of macro-industry are common to micro-enterprises, but due to diversified business development, the hierarchy of smart manufacturing for enterprises is more refined. Such micro elements are called capability elements in the process of enterprise smart manufacturing upgrade, and the hierarchy of differential characteristics due to different evolutionary degrees of capability elements is called smart manufacturing hierarchy. The existing research on the selection of capability elements for smart manufacturing hierarchy evaluation mainly involves the following aspects. First, the evaluation of key core technologies for digitalization, networking and intelligence. To determine the current development status of smart manufacturing by assessing the maturity of the key core technologies that make up the smart manufacturing technology system, mainly by analyzing the information technology in the digitalization stage[11]. Foreign Data Management Maturity Model (DMM), Data Management Capability Assessment Model (DCAM), Data Management Capability Maturity Model (DCMM) developed in China, etc., mostly evaluate data strategy and governance, data quality and security, platform architecture and other elements, and classify smart manufacturing into initial hierarchy, managed hierarchy, robust hierarchy, quantitative management hierarchy and optimization hierarchy according to the specific status of data capture, utilization and management degree; The evaluation of technology-oriented smart manufacturing in the networking phase takes network interconnection technology as the main object of assessment, and the Industrial Internet Platform Evaluation Method released by the Ministry of Industry and Information Technology in 2018 has specific indicators and corresponding evaluation methods, which provide a basis for the selection of the advantages and disadvantages of the platform construction of the industrial Internet, and also provide guidance to enterprises on how to effectively build industrial Internet platforms[36].

The key core technology represented by the intelligent stage is artificial intelligence technology (AI), which can empower smart manufacturing to achieve self-learning and self-decision, and China follows the AI Index released by the United States in 2017 and the 2018 China AI Index released in 2018 to measure the development of AI in China. The second aspect is the evaluation of specific industry sectors for manufacturing. Research in this area divides manufacturing into discrete and process-oriented manufacturing based on the differences in the material forms used in the production process[37]. The Industry 4.0 maturity assessment model for discrete manufacturing industries is assessed in terms of four dimensions of product, customer, operation, and technology enablers and five dimensions of strategy, leadership, management, culture, and employees at the organizational level[38]. As for the characteristics of process-oriented enterprises with smooth production process, efficient information feedback and low error rate, the related research is carried out from the aspects of intelligent technology, intelligent production and intelligent application[39].

3. Summary

In recent years, scholars have affirmed that smart manufacturing is not a first-order linear "non-smart manufacturing-smart manufacturing" transformation from both macro and micro perspectives. Rather, it is a multi-paradigm and multi- hierarchy systemic improvement process arising from the joint action of multiple elements. Identifying these elements in this process, clarifying how the elements work and the important connection between the elements and the development of smart manufacturing in enterprises are issues worth thinking about. Existing studies have analyzed the factors affecting the hierarchy of smart manufacturing from multiple perspectives and defined them as capability elements. From a systematic analysis, these capability elements can be summarized as strategic capabilities related to organization, talents and ideas at the abstract level, which have an important guiding role in the concrete implementation of smart manufacturing transformation and upgrading. The specific level can be divided into technology and resource capability. The technology capability is the institutionalization and integration of various combinations of modern emerging technologies to achieve data filtering, integration, protection, application and driving of hardware devices in the manufacturing process, while the resource capability is reflected in the degree of investment in advanced manufacturing equipment suitable for manufacturing and the construction of industrial Internet in the process of intelligent development of enterprises. Overall, the first three capability elements can be collectively referred to as the antecedent elements of enterprise smart manufacturing upgrade. Through the joint action of the antecedent elements to empower the various aspects of manufacturing to enhance the synergy of the industrial chain as the consequential capacity elements of smart manufacturing. It is more comprehensive and systematic to measure the hierarchy of smart manufacturing from the antecedent-consequence perspective. Furthermore, based on the specific enhancement of the aforementioned capability elements, the development of smart manufacturing in enterprises can be divided into different hierarchies, and there are differences in the characteristics of smart

manufacturing reflected in different hierarchies. But basically, it involves the process of single-latitude to multi-dimensional, abstract to concrete, and cut-off to comprehensive development. The current research on this issue, the hierarchical division of China's Smart Manufacturing Enterprise Maturity Model is of great theoretical and practical significance, and the hierarchical characteristics from the planned hierarchy to the leading hierarchy are highly compatible with the current industrial smart manufacturing development paradigm process. The core business process management at the planning hierarchy and the data sharing among single businesses at the specification hierarchy are highly similar to the digitalization of production factors through the introduction of digital technology in the development paradigm; the data integration and sharing of multiple businesses at the integration hierarchy is in line with the highly integrated networked production and manufacturing by building industrial internet and introducing advanced manufacturing equipment; the basic model of decision making based on data mining and processing at the optimization hierarchy and the innovation-driven production management based on decision making model at the leading hierarchy are very much in line with the evolutionary characteristics of the intelligent development paradigm(The overall concept diagram is shown in Figure 3).

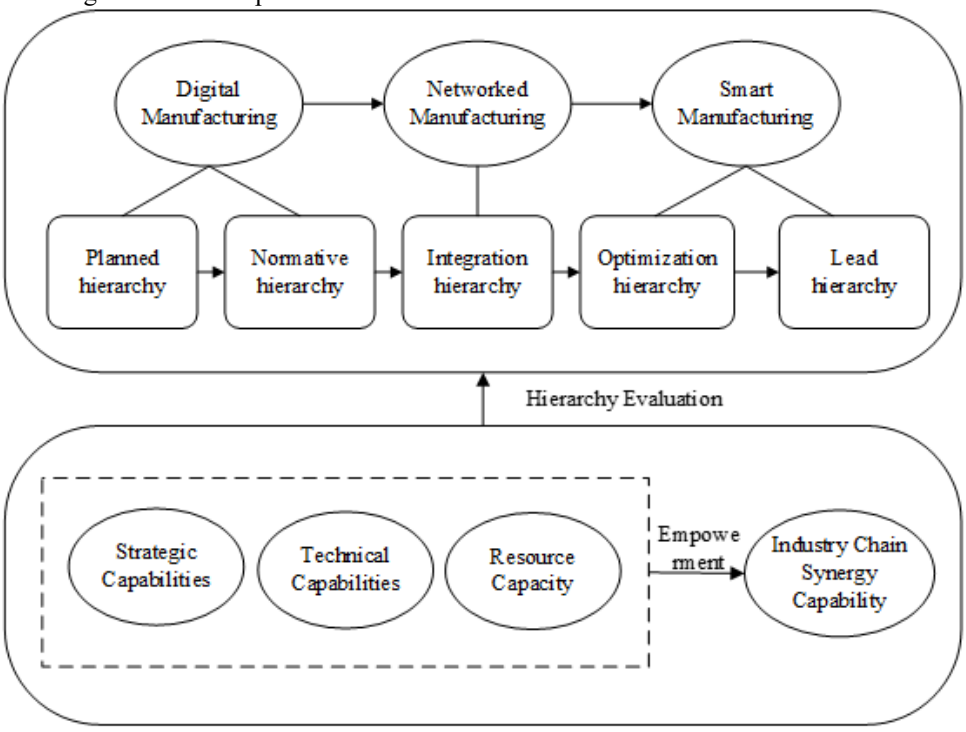


Figure 3. General concept diagram

On the basis of related research, the capability elements for smart manufacturing upgrading of manufacturing enterprises are refined and the linkage between the layers and paradigms, and the capability elements to the hierarchy of smart manufacturing is established. Future related research can further dissect the specific linkage between capability elements and hierarchy based on the role of capability elements on the hierarchy of smart manufacturing.

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