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Original Paper

A Review of Research on Networks of Modular Production

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Abstract

With the development of science and technology, the deep integration of products and technologies has made modularity in the field of industrial products has achieved good results, from IBM-360 computer to Volkswagen's MQB platform can be seen, in various industrial fields, the research and practice of modular production network has become one of the focuses of industrial upgrading. Based on the current research needs, the existing modularization literature is reviewed from three aspects: industrial modularization, industrial cluster modularization and modular production network.

Keywords

modularization, industry aggregation, industry modularization

1. Introduction

In today's world, science and technology are developing rapidly, the global situation is changing rapidly, digital, artificial intelligence and other information technologies are constantly reshaping the industrial development trend, and the rapid and dynamic competitive environment is also constantly promoting entrepreneurs to innovate and develop new business paradigms and industrial organization forms. At the same time, factors such as the gradual blurring of industrial boundaries and the rise of customer customization demand have spawned a new industrial value chain system and ushered in the modular era.

The research on modularity theory can be traced back to the concept of "complexity architecture", which was proposed by Herbert, an American management scientist. Simon came up with it in the 1960s. He used clocks and watches as an example to analyze the methods of solving complex problems by independent subsystems, but did not put forward the concept of "modularity". After the large-scale modular production of IBM computers, the academic community began to pay attention to the modular production mode, and its theory and mechanism were discussed and studied. In 1997, Baldwin and other scholars published a paper "Management in the Modular Era" and proposed the definition of

modularity for the first time, arguing that modularity is a process of decomposing complex things and turning them into relatively simple units with independent functions and operation capabilities (Baldwin & Clark, 1997). On this basis, Japanese scholars such as Masahiko Aoki have made a clearer explanation of modularity. He believes that module is a semi-autonomous subsystem in a large system, and "subsystem" refers to a more complex system that can be combined with other subsystems in the system according to certain standard requirements. "Semi-self-discipline" means that the subsystem has certain room for adjustment and improvement when it adapts to the requirements of the unified specification. "Modular decomposition" refers to the decomposition of a complex system into multiple independent subsystems according to certain standard requirements, and "modular centralization" refers to the combination of independent subsystems into a more complex new system (Aoki & Ando, 2003) with reference to certain requirements.

Since then, the academic community has officially started the modular systematic research stage. Since the 1990s, the fruitful development of modularity in various fields has also ushered in a research climax, and these studies have been successively applied to product development, technological innovation, organizational behavior and industrial development and other fields, and gradually formed product modularity, production modularity, management modularity and industrial modularity theories. However, after reviewing the literature, it is found that most scholars carry out research from the direction of modularity, a certain industry or service industry, etc., and lack of research on the overall industrial modularity under the current environment. Based on the research background of modularity and the significance of The Times, the original intention of this paper is: first, to grasp the evolution path of modularity production network theory as a whole and understand the latest research and development trend; The second is to explore the possible research direction in the future, hoping to provide academic guidance for the later generations.

2. Modular Theory and Its Characteristics

2.1 Modular Theory

In the era of information technology and economic globalization, it is also an era full of uncertainty and complexity. For this reason, scholars believe that modular design can be used as a solution to the increasing complexity of products, organizations and industries (Asan, 2008; Schilling, 2001)

At present, the concept of modularity has formed two mainstream schools, one is simon, Baldwin, Clark and Aoki Masahiko represented by the mainstream modular theory. In most of the literature on mainstream module theory, modularity refers to the ability of a product to be broken down into multiple components that can be separated and reassembled while maintaining integrity and functionality with each other (Baldwin & Clark, 1997). As long as it is connected according to the established setting standards and interfaces, the innovation of the entire product or system can be realized by changing one or some of the components, without the need to adjust or modify the other parts of the product. Therefore, modularity is implemented in a relatively stable interface standard. The other is the modified

modularity theory represented by Ernst and Chesbrough. Scholars represented by Ernst and Chesbrough believe that the development of modules requires a broader knowledge reserve, and the essence of modularity is the exchange of knowledge. Knowledge exchange promotes technological progress, and it can be said that technological progress will be repeated throughout the whole modular process. In order to achieve better benefits, modular systems may need to break the original structure, so there is no relatively stable interface standards. The two theories seem to be opposite, but in fact they are relatively complementary views (Bai, 2020). The modular decomposition construction needs to be completed under certain design rules, which is the basis of constant. However, with the Internet, big data into all walks of life, the whole society is in a stage of rapid development, consumer demand and product change speed continue to accelerate, product modular design rules may also change. Thus, change and unchange have always revolved around the evolution and development of modularity.

2.2 Modular Features

Modular design rules include: clearly defined and free design. Clear regulations include structures, interfaces and standards. The structure determines which modules are the constituent elements of the system and what role the modules have. Interfaces specify how modules interact, relate to each other, and exchange information. Standards are used to verify that the design of a module complies with the rules. Free design is to allow designers to freely play the design within the module under the conditions of complying with clearly specified conditions (Masahiko, 2003).

Due to the processing method of decomposing a complex system into multiple independent modules, modularity defined by these methods has the following characteristics:

(1) Independence of functional modules and knowledge modules. According to the standard of modular design, each decomposed sub-module has the independence of physical form, each sub-module represents a certain function in the system, and the functions of the modules are independent of each other and will not coincide. Relative to the design and production of sub-modules, each company has its own tacit knowledge, manufacturing sub-modules in the black box, and does not need to think too much about the production and contact problems of other modules. In this context, each company will strive for excellence in its own module areas, pooling knowledge and resources to improve technology in proprietary areas. Therefore, in a modular system, the overall performance can be improved through one or more modular innovations. This not only reduces the cost of innovation, but also improves innovation efficiency.

(2) Module substitutability and collaborative non-specificity. Each module in the modular system has different functions, and they are combined into a complete system according to the interface and standards, and ensure effective operation. Depending on the function, there are both general and special modules. The general module is the basic function that can ensure the use of the product, and the special module has a certain specific function. Special modules can not be used alone, need to be combined with general modules, by increasing and reducing the number of several special modules, rich module combination and product functions, to meet the customization needs of different users. At

the same time, the single module transformation in the universal module can also improve the entire product system, not only to maintain the integrity of the product, but also to achieve low-cost product technology upgrading. Modular technology facilitates the substitution of product parts and contributes to the emergence of alternative economy (Masahiko, 2003). The fungibility of modules makes each module not dedicated and has collaborative non-specificity. This nature changes the relationship between module function and structure: that is, a function can correspond to a variety of modules, and a product can also be combined with multiple parts, for example: mobile phones can use 128G memory, or 256G memory. This nature also changes the relationship between the module function and the product, that is, a module can also be used for a variety of products, for example: liquid crystal display can be used for computers, can also be used for mobile phones. The substitutability of modules broadens the boundaries and life cycles of products, and the collaborative non-specificity of modules blurs the boundaries of industries. These two characteristics make modularity have unlimited economic benefits in terms of innovation.

(3) Openness and self-coordination of the modular system. The modules of the system are produced in accordance with the pre-designed system framework, which not only ensures the independence of each module, but also ensures the integration and integrity of the system functions. Therefore, as long as the design and production are carried out in accordance with the design rules, the system can constantly add new module components. It can be said that modular technology provides an open platform for product systems. The system can take advantage of this openness by continuously adding or replacing modules to maintain the vitality of the system. Of course, this openness may bring some negative problems, for example, the design of some modules themselves is not perfect, and there will be certain risks in introducing them into the system. Since the modules themselves are independent of each other, and the design rules of the system will become more and more perfect, so even if some modules themselves have defects, other modules will achieve good self-coordination under the guidance of the design rules. The openness of modular system provides the path of knowledge acquisition for innovation. In the process of innovation and creation, knowledge and information acquisition is very important.

Speed up product innovation. With modularity, end users can generate additional value by mixing and matching components to meet different functional requirements. In this way, the modularity of the system can provide users with a variety of products. Manufacturers can improve the assembly efficiency and obtain higher benefits through the modular design of products. However, under the design rules, the modules in the product are independent of each other, and the other modules in the system will not be changed because of the change of one module (Baldwin & clark, 1997). Therefore, optimizing the subsystem does not necessarily optimize the overall system performance.

2.3 Function of Modular

(1) Enhance the flexibility of product innovation. Simon (1996) believes that modular architecture reduces the complexity of products by breaking them into loosely coupled components and connecting

them with each other through pre-specified interfaces. It also increases the design flexibility for later product innovation. Flexibility is achieved by replacing components in a single design hierarchy. Although not all products are decomposable in the real world, the ideal modular architecture provides a path for one-to-one mapping between product functional elements and physical modules. However, some scholars believe that modularity does not reduce the complexity of products. Through case studies of different industries, Stadenmeyer finds that modularity increases the complexity of product development activities when applied to the product production process. (Staudenmayer et al., 2005)

(2) Diversify investment risks. Reduce research and development costs. Since each module in each modular product has a certain independence, it is possible to innovate and upgrade the entire product by innovating on a single module. Masahiko has also pointed out that after modularizing the product, each module may enable "back-to-back" independent competitive research by one or more teams at the same time. In this process, the manufacturer shares the risk with multiple suppliers. Modular production not only reduces the risk of uncertainty, but also improves the success rate of research and development. This risk dispersion is mainly manifested in two aspects: First, enterprises are in the common cognition of the standard interface for production innovation, R & D enterprises do not need to collect all the information of the product, only need to concentrate on improving the performance of the responsible module. Second, each module's information is a "black box" relative to other modules, independent and closed. The innovation of the module is to further process and refine the information in the module, and improve the performance on the basis of the original product, which makes the product more confident of the market after improving the performance, because the original product has been recognized by the market.

When the product has the technical separability, the enterprise will modularize the product in order to pursue economic benefits. At the organizational level, product modularity will certainly bring about changes in the internal division of labor and organizational structure of enterprises. Such changes have caused some scholars to analyze the impact of modularity from the perspective of industrial organization, which will further change the relationship between clusters and production networks.

3. Research Status

3.1 Domestic Research Status

Product modularization development to a certain stage, will form a certain organizational structure, the formation of industrial modularization; When the enterprises in the industrial cluster are regarded as independent individuals, these individuals can be combined into a complete system, it is a modular industrial cluster. When industrial modularization has evolved into a global production network has formed a modular production network (Peng, 2009). The development and research of modularity are mainly carried out from these aspects.

3.1.1 Industrial Modularization

In today's world, the economic situation is severe and complex, and industrial upgrading and

transformation cannot be separated from the modular creation of products and industries. In the early stage of industrial development, it is mainly modularization, in the middle stage, it is module re-integration, and in the late stage, it is the expansion of the application field of modules. Research is of great significance for leading the scale of the industry and assisting in the adjustment and upgrading of the industry (Zhang, Qiao, & Song, 2016). Zhang and other scholars believe that only through the vertical decomposition and horizontal integration of the vertical integration industrial chain through modularization can industries achieve effective integration in a wider range and eventually form a complex industrial network with new industrial attributes or new formats (Xiao & Zheng, 2012).

Most scholars put forward targeted suggestions and improvement methods from the perspective of an industry. From the perspective of the education industry, Li Jun and other scholars compared the modular reform of vocational education in Britain and Germany and concluded that the reform of vocational education paradigm should be carried out in accordance with local conditions and step by step (Li & Yang, 2023). Yu believes that the high-speed rail system is decomposable and integrated, and it is necessary and feasible in terms of modular design and production (Yu, 2018). Modularity is one of the important trends of the automobile industry towards the era of new energy vehicles, which makes the automobile industry gradually evolve from the dominance of integrated product architecture to the dominance of modular product architecture (Tian, 2015). Therefore, most scholars start their research from the automobile industry. Taking FAW-Volkswagen as an example, scholar Zhao Ziyu discussed the impact of modular production on the spatial organization of the automobile industry cluster at the local - regional scale. He believed that the economies of scale brought by modular production could overcome the transportation cost to a certain extent, leading to the decrease of the dependence on the production of the host country and the decrease of the spatial agglomeration of parts suppliers after the industrial transfer of large vehicle groups. Modular production will reorganize the organizational structure of regional production network, resulting in a competitive advantage of "beyond local", and the effect of scale economy, knowledge and technology sharing and enterprise organization strengthening will jointly drive the spatial organization reconstruction of automobile industry clusters under modular production (Zhao, Wang, & Chen, 2021). Wang et al. discussed the interaction between industrial modularity and discontinuous innovation in combination with the automobile industry, and found that the relationship between them is not only positive, but also significant in the long run (Wang, Huang, & Lin, 2018).

Integrated circuit chip is the industrial brain, but also China's current urgent need to solve and overcome the problem, so more scholars will also study the role of modularity on the industry from this direction. Wang scholars proposed that the chip design and manufacturing mode has developed into a chipless design mode. China's current chip core research and development field is weak, and it is at a disadvantage in the "trade war" in the face of the United States. There is an urgent need to use the chipless design mode, combined with the modular research and development production mode, to form a large network ecology around the chip design of core enterprises, break through the technical barriers

of chip research and development, and promote the rapid improvement of China's integrated circuit chip industry (Wang, 2019). With the in-depth development of economic globalization and information age, the high-tech industrial chain has shown the characteristics of modularity, and the economic organization structure has also developed to a modular structure, and has gradually become the leading industrial organization model. The difference of resources and knowledge capital makes the heterogeneity of modules prominent in the modular network, and heterogeneity has the effect of amplifying comparative advantage. The existence of heterogeneity in the modular industrial chain further amplifies the comparative advantage between China and the United States in the trade of high-tech products, resulting in the effect of mutual complementarity and joint enhancement of interests between China and the United States in the trade of communication equipment (Liu & Su, 2019).

Under the background of the division of labor and deconstruction of the industrial value chain, the production and operation activities of enterprises are no longer limited to their own resources, but spread to the integration and utilization of the entire network resources. Therefore, Wang and other scholars proposed four dimensions of enterprise modularity capability, namely vision planning capability, rule design capability, module integration capability and relationship management capability, and on this basis proposed a measurement scale of enterprise modularity capability (Wang & Ren, 2021). In addition, there are also scholars from the modular perspective, based on modular production network industrial chain integration of theoretical research; On this basis, the network industry chain model of Anhui automobile industry was constructed (He & Zhang, 2013). Under the modular production mode, the new characteristics of the competitive advantage of enterprises are studied (Zhang, Tang, & Guo, 2013). Based on the modular theory, a theoretical model of collaborative innovation in the new energy automobile industry is constructed, thus promoting the improvement of the overall innovation ability of the industrial chain (Liu, Wu, & Sun, 2012).

In addition, with the technological breakthrough and industrial upgrading of strategic emerging industries showing significant modular characteristics, strategic emerging industries also participate in and create modular industrial organizations, join the modular production network, and actively utilize global high-quality resources to gradually optimize and upgrade the industrial structure (Zhang & Bai, 2018). Among the strategic emerging industries, the new energy industry has the highest degree of modularity, the new energy automobile and the new generation of information technology industry has a high degree of modularity, and the biomedical industry and the new material industry has a relatively low degree of modularity.

3.1.2 Industrial Cluster Modularization

Many scholars believe that modularity is the essence of industrial cluster and the expansion form of value chain, and put forward the concept of value module. With the development of socialized mass production, industrial division of labor and specialization are deepening. Scholars at home and abroad generally believe that the division of labor and specialization help to improve the efficiency of social

production. At present, industrial cluster has become the "third mode of production organization" co-existing with market and enterprise, and its formation and development are often based on division of labor and specialization. The continuous innovation and development of modular production mode on the basis of industrial division of labor not only breaks through the combination mode of traditional industrial chain and the production mode of traditional enterprises, but also profoundly changes the rules and paths of industrial cluster evolution (Yan, 2011). The path of industrial cluster modularization is the interaction of technology modularization, product modularization, market modularization and organization modularization. Modular industrial clusters have high organizational efficiency, which is mainly manifested as: innovation efficiency based on functional modules, coordination efficiency constrained by design rules, information transmission efficiency characterized by flat organizational structure, low assimilation efficiency guided by active innovation, transaction efficiency based on transaction cost reduction, and collaboration efficiency based on division of labor (Wang, 2011).

The modularization of industrial cluster organization can break the regional and industrial restrictions and form a modular value network with low transaction costs and high innovation ability (Cao, Li, & He, 2016). As a new mode of production, division of labor and organization, modularity is bound to have a profound impact on the upgrading of manufacturing clusters. Modularity leads to the transformation of the division of labor mode, governance mode and market structure of the global value chain, which brings new opportunities, new momentum and stage crossing in the path of cluster process upgrading, product upgrading, function upgrading and chain upgrading. This has certain enlightenment significance for realizing the upgrading and transformation of the manufacturing industry to "intelligent manufacturing in China" and "high-quality development" (Su, Liu, & Li, 2018).

3.1.3 Modular Production Network

Modular production network generally refers to an open network organization formed by connecting production and integrated manufacturers with contracts on the premise that products can be modularized. It is a new form of organization that ADAPTS to modular technology and information technology. As one of the most advanced forms of industrial organization, modular industrial network is of great significance in promoting the sharing of superior resources among enterprises, building innovation platforms and enhancing the competitiveness of enterprises (Zhang & Zhong, 2015). Many scholars analyze the collaborative innovation ability of industry from the perspective of modular network based on their own research fields. Liu Guowei and other scholars analyzed the industrial collaborative innovation ability from the perspective of four dimensions of innovation input, innovation output, environmental support and policy support, and believed that policy support contributed the most to collaborative innovation ability, while environmental support contributed the least (Liu, Shao, & Liu, 2021). Some scholars also believe that modular division of labor has a great impact on technological innovation, while modular collaboration has a relatively small impact on technological innovation (Cao, Zhang, & Liu, 2015). Some scholars also believe that industrial modularity and industrial innovation have a low level of coordinated development and show a fluctuating trend (Wang,

He, & Wang, 2014).

In the production network, the modular division of labor reduces the inter-organizational dependence, but does not affect the organizational activities and cooperation between modules. Therefore, in order to improve the collaborative innovation ability of enterprises, it is necessary to make use of the intermediary role of modularity to effectively connect the modular technical framework of enterprises, universities, research institutes and partners, and connect the relationship between the demand side and the supply side, so as to better enhance the industrial value (Wang, Chen, & Cheng, 2018). To some extent, the service modularization structure of industrial network will provide a technical platform for its risk formation path. Therefore, the axiomatization, loose coupling and network interface rule design of network node modules are optimized (Li, Shen, & Yu, 2019).

Based on the formation of modular production networks, many scholars also follow current events to understand the development form of emerging modular networks. Ge and other scholars found the modularization of value network, that is, in the creative industry cluster, creative enterprises cooperate in the form of different business modules, and carry out modular cooperation with their respective core capabilities as the link, forming a new enterprise value network system based on modularization. Through the interaction of the three value-added subsystems of industrial chain, supply chain and value chain, they form a complex comprehensive system of value network and create value (Ge & Gao, 2017). Ke et al. built an industrial value network division model based on the modular three-dimensional framework through the Beibu Gulf industry in Guangxi, and discussed the value enhancement path of industrial value network under the condition of modular division of labor (Ke & Shi, 205).

By comparing the service modularization value network governance mechanism of cigarette industry and dairy industry, Yu et al. believed that the difference of environment led to the different forms of the two industries' modularization dilemma, and proposed the corresponding service modularization value network governance mechanism (Yu & Shen, 2017). Min Hong proposed a clearer concept of enterprise modularity based on the analogy of "integration" and "specialization" (Min, 2017). At the same time of the development of the new modular network, the cross-industry integration of network modularity has also attracted the attention of researchers. Scholar Dong Hua proposed that the mutual penetration and reorganization of industrial chain modules of manufacturing and service industries can not only bring about industrial upgrading effect, cost saving effect, integration and innovation effect and knowledge spillover effect, but also change the original form of manufacturing industry, resulting in the emergence of a new cooperation network of capabilities and demands - service-oriented manufacturing network. It is further decomposed into service production value module, productive service value module, customer utility value module, and the functions of each value module (Dong, 2016).

3.2 Foreign Research Status

Foreign scholars have studied that modularity is the innovation driving force of industrial clusters and is conducive to eliminating the endogenous risks of industrial clusters (Ma, 2008). Modularity is a design attribute of product, organization, and inter-company network architecture; Modularity is a process that influences these designs while also shaping company boundaries and industry landscape; "Modularity" is a cognitive framework that guides the classification and interpretation of various economic phenomena, so modularity refers to attributes, processes and frameworks (Macduffie, 2013). Increasing efficiency and productivity are contemporary challenges facing industrial organizations, and product modularization is considered a strategic alternative to achieving these goals, capable of improving company domain or production efficiency (Piran, 2016). In addition, product modularity can also enhance an enterprise's competitive advantage (Kim & Shin, 2021). Different scholars have proposed the role of modularity from different industries. Some scholars, starting from the construction industry, have proposed a unified definition and practical guidelines for modules in construction projects to help managers organize project activities to achieve effective modularity (Gosling, 2016). From the perspective of urban transportation, based on the modular framework of service system, service modules and data sources can be determined to promote co-creation and innovation within the existing service system (Schreieck, Wiesche, & Krcmar, 2016). Similarly, foreign scholars also prefer to study the modularity of the automobile industry, and believe that modularity is an important factor in China's automobile industry. It has a positive effect on these variables that constitute firm relative positional advantage (ICao, Liu, Zhang, & Zhang, 2013). Moreover, through the sample analysis of 262 auto parts suppliers in China, the positive impact of modularity on enterprise performance is demonstrated again (Seyoum & Lian, 2018). Foreign scholars pay more attention to the role of modularity on performance, and believe that product modularity is the intermediary between customization demand and financial performance, which can promote enterprises to develop customized products (Persson & Lantz, 2022). Global modular production networks will also be studied from the information technology industry and manufacturing sector (Cao, Zhang, & Liu, 2012).

Domestic and foreign scholars have contributed a lot of excellent literature materials to the study of modularity, and also consider and analyze the economic utility of modularity for industrial upgrading from the perspective of different industries, especially the automobile industry. Domestic scholars have a high degree of research focus and will generate a lot of literature on a single focus, while foreign scholars seem to consider more personal preferences in their research, which has a certain relationship with the domestic and foreign research environment. Domestic studies on modularity pay more attention to the impact of modularity on the value chain of the entire industry, and use cases of specific companies or industries to study the value governance of modularity, while foreign studies pay more attention to the role of performance.

4. Brief Comments

Modular production network is different from the general network organization, it is with the maturity of modular technology and the development of information technology and gradually grow up and is not limited by the region, and has a close relationship with the decomposition and integration of complex products or complex technologies. Scholars at home and abroad have fully studied the modular production network from different perspectives, which is of great significance for reference. However, there are some fields that can be further enriched:

(1) Lack of large sample data, and cannot conduct empirical research with both static and dynamic data. Most of the existing literatures use cross-section data, that is, relatively static data, which cannot reasonably observe the changes between variables of the research object under the role of modularity, and the conclusions drawn will be relatively incomplete.

(2) The research scenario is too narrow, and there is a lack of articles to prove whether modularity brings positive and extensive effects in a general sense. Most of the articles choose high-tech manufacturing industries such as automobiles, IT information, and automation, ignoring the application scenarios and applicability of modularity in other medium and low-degree technology manufacturing industries or service industries, and failing to obtain a comprehensive mechanism and impact relationship of modularity.

(3) Lack of combination of modular research and social environment. With the iteration and new of artificial intelligence and AI technology, network technology will continue to penetrate into the low-end labor environment offline, and the current youth unemployment rate has reached 20%. Under such a background, how to improve the rationality of product modular design and ensure social stability is also a topic worthy of discussion.

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