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Micro-Mechanism Analysis of Computer Industry Division of Labor Modularization Based on Supramarginal Models

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Abstract: After the modularization of computer production technology in the last century, market value gradually dispersed from the integrated enterprise IBM, leading to a gradual transformation in the organizational structure of the industry. However, the implementation of technological modularization does not necessarily result in the modularization of industrial division of labor. This paper addresses the evolutionary problem of organizational modularization by constructing a supramarginal model and transforming it into a choice problem for division of labor structures. The modularization of product production technology provides a uniform standard for interfaces between various components of complex products, leading to positive transaction efficiency between module manufacturers and module integrators. As transaction efficiency improves, the production organizational structure shifts from integration to modularized division of labor. Based on this foundation, the paper analyzes the impact of industry modularized division of labor on individual welfare and market expansion.

Keywords: Product modularization, modularized division of labor, supramarginal analysis, computer

1. Introduction

Modules are generally defined as semi-autonomous systems with specific functions that can be integrated into more complex systems following certain rules through a standardized set of interface interfaces [1]. From a supply perspective, modularization technology specifies the standardization of interfaces between modules in advance, allowing modules to be designed and produced separately and then effectively assembled to form a complete system for consumption. This technology reduces the complexity of the product system during the production process, allowing different parts to be provided in a specialized manner, and compressing the time required for design and production. Product modularization merely indicates the technical feasibility of separate production of a certain product, without necessarily implying that this modularization extends to the external organization of the industry. Even when the final product has the technological conditions for modularization, companies can still choose to produce different modules within their organization using a self-sufficient approach, assembling them into a complete final product.

In the 1970s, products from various manufacturers in the computer industry were incompatible with each other, and even components of different computer models from the same company were incompatible. Although various components of computer systems were manufactured separately, the

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technical standards followed by each company were different and closed, meaning that standardized interfaces for modules had not yet been established within the industry. During this stage, companies tended to produce a range of modules, including operating systems, integrated circuits, software, external devices, in an integrated manner. This also meant that if a company wanted to introduce a new computer to improve technology, it had to design all the functional modules specifically for that type of computer. Therefore, the lack of standardized interfaces in the industry made it difficult for new companies to enter, as doing so would likely require providing an entire computer system, creating high entry barriers. Once the industry established a unified interface standard, the situation could change significantly.

After IBM pioneered the development of the modular IBM360 system, standardized interface rules emerged. In essence, the designers of IBM360 based the design of computer functional modules on explicit rules and implicit rules, with explicit rules being "visible design rules" determining how different modules work together. Each design team created modules containing implicit knowledge while following explicit rules. The introduction of these rules allowed product modules to be more freely combined, enabling consumers to upgrade or add new modules based on specific and diverse preferences. This system's launch brought significant success to IBM, and for many years after the 1970s, the market share in the mainframe computer market was largely dominated by IBM. IBM's excess profits led to antitrust litigation, and since IBM had a majority of the market share at the time, it had to moderately open up its technology standards, signifying a degree of standardization in the industry. In this scenario, companies had two choices: either continue with an integrated strategy, self-sufficiently producing the entire product system, or specialize in the production of certain modules or components, and then assemble them based on the standard interface rules to obtain a complete product. In reality, many hardware and software manufacturers entered the market, competed with incumbents through local module innovations, and gradually shifted market value. As a result, the computer industry moved away from IBM's monopoly [2-4]. With the progress of this process, the computer industry has now formed about 16 sectors where companies are closely connected, but no single company can independently manufacture complete computer systems.

However, the modularization of product production does not necessarily lead to corresponding changes in production organization. Even if production technology allows products to be produced in a modular form, it does not necessarily mean that companies will shift from an integrated production organizational structure to inter-enterprise modular division of labor. Therefore, the conditions and motivations for the evolution of this organizational structure, and the economic consequences accompanying organizational change, are worth considering. For the issue of production organization evolution, supramarginal analysis provides a powerful mathematical method for studying how participants in the market make decisions regarding the division of labor (supramarginal decisions) and production quantity (marginal decisions) in a general equilibrium framework. However, the application of this method in previous relevant research has not been widespread. In addition, in previous supramarginal models, scholars often assumed that the number of participants in the market was exogenously given, which is not conducive to analyzing the impact of changes in production organization on the employment that the industry can create. In this paper, the number of market participants is not exogenously given but can be determined endogenously by the specific production organization.

2. Literature Review

Modularization has implications both from the perspective of product design and manufacturing and from the angle of the evolution of production organization. From the viewpoint of product design and manufacturing, Baldwin and Clark (1997) defined modularization as the process of producing complex products by using a series of subsystems that can be independently designed and operated

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as a whole. Modularization not only implies that production processes can be decomposed and carried out independently but also that they can be integrated to perform their intended functions. Therefore, modularization must adhere to "Visible Design Rules," which include architecture, interfaces, and standards [4]. Organizational modularization is, in fact, a pattern in the evolution of division of labor where non-hierarchical entities replace hierarchical organizations. In this process, complex production tasks originally undertaken by a single enterprise are now distributed among multiple enterprises but can ultimately be integrated into a complete final product. While the shift in production organization towards modularization is based on the premise that final product production can be modularly disassembled and integrated, the two are not equivalent. This is evident from the field research conducted by Cheng Wen and Zhang Jianhua (2011), which shows that product modularization and organizational modularization do not evolve synchronously. The transformation of production organization is constrained or promoted by various other factors [5]. Hu Xiaopeng (2004) points out that the economic structure of modularization is a harmonious coordination of centralization and decentralization, where horizontal and vertical division of labor are organically combined. The driving force for the evolution of an economic system into a modular structure lies in the transition of dominant resources in the economy from primary resources such as capital and natural resources to advanced resources like reputation and social capital. Furthermore, the advancement of the economic structure and the accumulation of advanced resources are mutually reinforcing during this evolutionary process. Su Jing and Lou Zhaohui (2005), from the perspective of emerging classical economics, provide an explanation of modular division of labor and analyze the economic efficiency of transaction costs and modular organization [6]. Sun Binbin (2006) extends the traditional Becker-Murphy division of labor model to explain the reasons for organizational change. He suggests that coordination issues are closely tied to division of labor. Assuming that coordination costs are a quadratic function of coordination time, deepening division of labor can bring the benefits of specialized economics but may also lead to uneconomical division of labor. Therefore, coordination costs are an important factor influencing enterprise organizational change [7].

3. Approach and Methodology of Supramarginal Analysis

The decision of whether producers choose to become an integrated company, where different departments provide various functional modules and then integrate them, or choose to specialize as suppliers or integrators of specific functional modules essentially involves the evolution of division of labor. In the development path of economics since Marshall, mathematical analysis has become an important research methodology in economics. Economic growth studies often appear in the form of mathematical models. Factors that are easily quantified, such as technological progress, capital accumulation, and labor, have received significant attention from economists. However, division of labor, due to its topological nature, is challenging to represent by a single numerical value, even though it is a crucial factor that can enhance efficiency in the production process. It wasn't until a group of economists represented by Yang Xiaokai and Huang Youguang pioneered the new classical economics and utilized the method of supramarginal analysis that the problem of division of labor evolution was mathematically modeled [8]. This paper employs the supramarginal analysis method to investigate how the computer industry evolved from technological modularization to trigger industrial organization modularization. It studies the endogenous decision-making of producers regarding specialization in division of labor. Furthermore, it analyzes how market value in the history of the computer industry in the last century was dispersed among module suppliers in various fields. This explanation shows how the industry's division of labor structure transitioned from a vertically integrated market equilibrium to a coexistence of independent module suppliers and integrators in market equilibrium.

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The general approach of supramarginal analysis is roughly as follows [9]. Every individual in the market is both a producer and a consumer. Each person has predefined production functions, utility functions, and faces constraints such as time and budget. Additionally, they have three decision variables for each product in the market: self-sufficiency, sales quantity, and purchase quantity, all of which are greater than or equal to 0. Among these, an individual's self-sufficiency and sales quantity sum to their production quantity. The production function is influenced by the degree of specialization and the elasticity of final products' use of intermediate products, while the individual utility function is related to the self-sufficiency, purchase quantity, and transaction efficiency of the product. The division of labor structure in the market is formed by the different decisions (zero or positive values) of each individual for these three variables for various products. For example, if someone's sales quantity for a commodity 'x' is equal to self-sufficiency (both are zero), but the purchase quantity is greater than zero, it implies that they do not produce 'x' but need it as a final product. Due to the existence of the Coase theorem (to avoid additional transaction costs, people will not simultaneously buy and sell the same product), this means that if someone produces the final product 'x', their self-sufficiency for 'x' must be greater than zero, and the purchase quantity and sales quantity cannot be simultaneously positive. Based on the Coase theorem, many inefficient division of labor structures can be eliminated, and if exogenous comparative advantage is considered, some structures can be further excluded. Among the remaining structures, the optimal values of the three decision variables for each product are determined using an individual's production function, utility function, and constraint function. Then, the social utility of each structure is compared, and the division of labor structure with the highest utility is selected.

4. Establishment of the Supramarginal Model

Following the framework of the supramarginal model, each manufacturer engages in production for the consumption of the final product, a computer. We consider market participants as a collective of both producers and consumers, with each individual being a "producer-consumer." Their utility is a function of the quantity of final products, defined as $u=y+y^d$. Here, y represents the self-sufficiency of computers, and y^ddenotes the purchase quantity of computers. For individuals engaged in module production, they do not directly produce the final computer product, so y=0, and their utility function is $u=y^d$. On the other hand, individuals who produce computers by integrating modules have a utility function $u=y+y^d$.

For the sake of simplification in the model, we assume that the computer is composed of two modules: Module 1 and Module 2. Module 1 and Module 2 are produced by module manufacturers and are then integrated into a complete final product either within a firm's integration department or through integrators in the market. To focus on the main topic of this paper, we do not endogenize the number of modules. We assume that both Module 1 and Module 2 are essential components of the final computer product, meaning that the absence of either would render the final product non-producible. In reality, some functional modules exist to cater to diverse consumer needs, and adding them can enhance utility. However, the absence of these modules does not prevent computer production. We do not consider such modules in this paper. We denote the individual production quantities and supply quantities of Module 1 and Module 2 produced by module manufacturers as X_1^p, X_2^p, and X_1^s, X_2^s, respectively. As independent modules cannot function individually and need to be integrated to produce the final computer, the module manufacturers provide the entire quantities produced for the purpose of producing the final product. Hence, the module production function is also the module supply function, i.e., $X_1^p=X_1^s$ and $X_2^p=X_2^s$. The production function of each module manufacturer is denoted as $X_1^s=L_1$ and $X_2^s=L_2$, where L_1 and L_2represent their individual levels of specialization. Module 1 and Module 2 are complementary in a 1:1 quantity relationship, and thus the production function of the final product: $y^p=y+y^s=L^a\min\{X_1,X_2\}^a$. Here, L represents the labor

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supply of module integrators, which signifies their level of specialization, and a represents the elasticity of output quantity of final products with respect to the input quantity ($0<a<1$). We assume that each worker produces only one product (Module 1, Module 2, or the final product), so the level of specialization for each person is 1. The module and final product production functions established above are presented in their general form. In the specific problems discussed later, their forms may vary:

(1)We refer to the division of labor structure where an integrated company is responsible for the production and integration of various modules as Structure A. The integrated production model can save transaction costs in the market but incurs substantial organizational costs because the company needs to establish three departments to provide the final product. Department 1 and Department 2 produce Module 1 and Module 2, respectively, with the number of workers in each department being m_1 and m_2. The production functions of individuals in these departments are as follows: $X_1=L_1=1$, $X_2=L_2=1$. The third department has only one person, responsible for integrating the modules from the other departments. We assign a special status to this person, the employer, and will discuss the employer's decision later. As the company's scale increases, the organizational costs associated with organizing the various departments in production activities rise, resulting in a reduction in organizational efficiency. Due to the existence of organizational costs, factors and module inputs cannot be completely converted into final product output. We assume that only multi-department companies incur organizational costs, and these costs increase with the size of the enterprise. Consequently, we assume that organizational efficiency follows the form: organizational efficiency=$1-c(m_1+m_2)^{0.5}$, where c is the organizational cost coefficient ($0<c<1$), and m1+m2 represents the scale of the enterprise. Therefore, in the presence of organizational costs, the production function for integrators who integrate modules produced by Department 1 and Department 2 in a 1:1 ratio is $y^p=y+y^s=L^a\min\{m_1X_1,m_2X_2\}^a\ [1-c(m_1+m_2)^{0.5}]$. We will now explain the employer's decision: According to the Coase theorem, the employer's utility level u equals the portion of the final product they produce for their own use, i.e., y. Following the principle of utility maximization, our model can endogenously determine the number of department workers employed by the employer.

(2) We refer to the division of labor structure in the industry where there are specialized firms responsible for single module production and specialized firms for module integration as Structure B. The emergence of standard interfaces undoubtedly created conditions for module trade between manufacturers. If manufacturers provide complete product systems through integration, they face large internal organization and high management costs. However, if the efficiency of market transactions between manufacturers improves, it may lead to separate manufacturers for producing specific modules and integrators who combine these modules. We use $B(X_1/y)$ to represent the module manufacturer that produces and supplies Module 1 and purchases computers. We simply consider the module manufacturer as a manufacturing team composed of individuals who produce the same module, without having an employer as in (1). The team members are equals, and they gather together solely to save transaction costs in dealing with module integrators. When module integrators purchase the same module, they do not need to separately locate each scattered individual; they can conduct a single transaction with the module manufacturer. Similarly, we use $B(X_2/y)$ to represent the module manufacturer that produces and supplies Module 2 and purchases computers. We also use $B(y/X_1X_2)$ to denote the integrator that procures modules to assemble the final product. Their production functions are set as follows: the total output of Module 1 produced by the Module 1 design team (rather than individual output) is $TX_1^p=m_1X_1^p=m_1L_1$. Here, $m_1$is the number of team members, and $L_1=1$. The total output of Module 2 produced by the Module 2 design team is $TX_2^p=m_2X_2^p=m_2L_2$. m_2 represents the number of team members, and $L_2=1$. The total production functions of the two module manufacturers do not include factors related to organizational efficiency because we have assumed that organizational costs exist in multi-department companies. The

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production function for y is $y^p=y+y^s=L^a\min\{k\cdot TX_1^d, k\cdot TX_2^d\}^a$. Here, k refers to the market transaction efficiency for modules ($0\leqslant k<1$), while the transaction efficiency in the transaction of final products, computers, is 1. The appearance of market transaction costs (i.e., k<1) is a "penalty" imposed on producers for not adopting integration but rather opting for the division of labor by trading modules in the market. For the sake of simplifying the model, we ignore transaction costs in the market transaction of final products. This does not affect the content we wish to explain.

After setting the production functions and utility functions for various entities, we provide an explanation for the equilibrium state in each division of labor structure. Under each division of labor structure, producer-consumers reach a general equilibrium through the Walrasian mechanism, where the supply and demand for each module and the final product are in equilibrium. In the supramarginal model, one simplification method employed to endogenously determine wages and price ratios between various products is to assume equal utility levels for individuals in the equilibrium state, referred to as the "equal utility condition." This is because if utility levels are unequal, individuals would exit low-utility specialization choices and enter high-utility specialization choices. This assumption implies that there are no exogenous comparative advantages. In Structure A, we assume that the equilibrium utility levels for both the employer and employees are equal, which, in turn, endogenously determines the wage w and the price ratio of the final product P_y. In Structure B, we assume that the equilibrium utility levels between the module design teams and integrators are equal, which endogenously determines the price ratio of Modules 1 and 2, P_1, P_2, and the final product price, P_y.

Based on the model settings, the production and decision problems for each division of labor structure are as follows:

1. Structure A:

Employer's objective function: $\max u = y$

Individual production functions for X_1 and X_2: $X_1^p= L_1, X_2^p= L_2$, where $L_1=L_2 = 1$

Final product y production function:

$y^p = y + y^s = L^{0.5}\min\{m_1X_1^p, m_2X_2^p\}^{0.5}[1-c(m_1+m_2)^{0.5}]$

(To simplify the model, let a=0.5 in the final product production function, and the same applies below.)

Employer's budget constraint: $P_y y^s = w(m_1 + m_2)$

Employee's objective functions: $\max u_1 = {y_1}^d$, $\max u_2 = {y_2}^d$,

Based on their budget constraints: $P_y y^d = w$, their indirect demand functions are obtained: ${y_1}^d = {y_2}^d = \frac{w}{P_y}$

Supply-demand equilibrium condition: $y^s=m_1{y_1}^d+m_1{y_2}^d$

Equal utility condition: $u = u_1 = u_2$

2. Structure B:

$B(X1/y)$:

Individual objective function: $\max u_1 = {y_1}^d$

Total production function (total supply function): $TX_1^p=m_1X_1^p=m_1X_1^s=m_1L_1, L_1=1$

Individual budget constraint: $P_1X_1^s=P_y{y_1}^d$

$B(X2/y)$:

Individual objective function: $\max u_2 = {y_2}^d$

Total production function (total supply function): $TX_2^p=m_2X_2^p=m_2X_2^s=m_2L_2, L_2=1$

Individual budget constraint: $P_2X_2^s=P_y{y_2}^d$

$B(y/X1X2)$:

Individual objective function: $\max u = y$

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Final product production function: $y^p = y + y^s = L^{0.5}\min\{kX_1^d, kX_2^d\}^{0.5}$, L=1

Individual budget constraint: $P_y y^s = P_1 X_1^d + P_2 X_2^d$

Supply-demand equilibrium condition: $y^s = m_1 y_1{}^d + m_2 y_2{}^d$, $TX_1^p = X_1^d$, $TX_2^p = X_2^d$

Equal utility condition: $u = u_1 = u_2$

5. Equilibrium Results and Analysis

1. Model Solution to Market Equilibrium:

Conditions	Structure	Equilibrium Solution
$k < \left(\frac{1}{c+(1+c^2)^{0.5}}\right)^2$	A	$u = u_1 = u_2 = \frac{w}{P_y} = \frac{1}{2\sqrt{2}} \cdot \frac{1}{c+(1+c^2)^{0.5}}$, $m_1 = m_2 = \frac{1}{2[c+(1+c^2)^{0.5}]^2}$
$k > \left(\frac{1}{c+(1+c^2)^{0.5}}\right)^2$	B	$u = u_1 = u_2 = \frac{\sqrt{2k}}{4}$, $\frac{P_1}{P_y} = \frac{P_2}{P_y} = \frac{1}{2}\sqrt{\frac{k}{2}}$, $m_1 = m_2 = \frac{1}{2}$

2. Equilibrium Analysis

According to the comparative static analysis of the super-marginal model, changes in the division of labor structure in the economy depend on which industry division of labor structure can provide a higher average utility to each producer-consumer. If modular division of labor results in a higher utility level for each producer-consumer compared to the integrated case, then producer-consumers will naturally shift from integration to modular division. How the division of labor evolves depends on which set of conditions corresponding to the structure is met. As the market transaction efficiency (k) of various functional modules increases, beyond a threshold related to the organizational cost coefficient (c), the industry division of labor structure dominated by the integrated production organization form will evolve. Initially integrated enterprise production will shift to independent production of various functional modules, which are then integrated into complete final products through transactions with specialized integrators. It's easy to observe that the higher the organizational cost coefficient (c), the lower the efficiency threshold required for the shift from integration to modular division. If we assume that c remains unchanged throughout this process, then the evolution of the division of labor structure induced by an increase in k will enhance the welfare levels of all market participants.

Furthermore, it should be noted that this paper does not exogenously specify the number of producer-consumers participating in the computer industry. However, as the production organization shifts from integration to modular division, market participants will increase. In the equilibrium solution of Structure A, the total number of market participants is the sum of the employees in the three departments of the integrated enterprise: $m_1 + m_2 + 1 = 1 + \frac{1}{[c+(1+c^2)^{0.5}]^2} < 2$. In Structure B, the number of participants that the market can accommodate is the sum of employees in the two module manufacturers and one integrator: $m_1 + m_2 + 1 = 2$. Although the number of market participants accommodated in Structure B is a constant in this context, this is merely a coincidence resulting from the functional settings of this paper, and it has no absolute significance but is only relative. Therefore, it can be inferred that the computer industry, after the transformation from integrated production to modular division, can absorb more market participants, creating more employment opportunities.

The emergence of industry-wide explicit rules for standard interfaces is a prerequisite for the modular division of labor in industrial organization. This is because without unified interface standards, trading between manufacturers regarding intermediate components is fundamentally impossible, meaning k=0, and independent module suppliers will not appear. Since IBM's explicit rules and technical standards were made public, k has become a positive value ranging between 0 and 1. If the market transaction efficiency of modules is extremely low, manufacturers, even when there are clear module design rules in the industry, will not proactively adopt the modular division of labor production strategy, but will continue to prefer to supply the entire computer system in an integrated manner. Such extremely low transaction efficiency may be due to a lack of smooth information exchange in the market or the reputation of new module suppliers has not yet been established, and sales channels are still not perfect. On the other hand, it may also be due to technical protection considerations by manufacturers designing and producing core modules, making it difficult for most integrators to trade with them. The designers of these core modules may be more inclined to adopt some form of vertical restraint that tends to be integrated. When modular division of labor crosses national borders and develops into an international division of labor, political risks will also have a significant impact on k.

6. Conclusion

In this paper, by constructing a super-marginal model, we transformed the issue of the evolution of production organization forms into a choice problem faced by each producer regarding the division of labor. Market transaction efficiency can lead to changes in relative utility levels between modular division of labor and integrated production. During the process of improving market transaction efficiency, once a threshold related to organizational costs within enterprises is exceeded, the utility level for each producer-consumer under modular division of labor will be higher than that under integrated production. Consequently, producer-consumers will naturally shift from an integrated production organization form to modular division. Throughout this transformation, the welfare levels of each market participant improve, and the number of market participants accommodated in the computer industry increases. Therefore, it can be argued that modular division of labor within enterprises is conducive to creating more employment opportunities.

The establishment of industrial parks by governments can reduce transaction costs between enterprises in terms of geographical location and information gathering, thus enhancing transaction efficiency. However, this is not the most critical prerequisite for promoting the modular division of labor in the production process of complex products. Only when various intermediate products produced by different enterprises adopt unified "interface" standards can transaction efficiency between enterprises become a positive value. Low efficiency in information flow between enterprises, imperfect credit mechanisms, and the potential negative impact of political risks associated with cross-border division of labor may hinder the formation of modular division of labor.

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