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Research on Artificial Intelligence (AI) as Production Factors

Wei SHE and Ke LI

Graduate School of Economics, Nihon University, 1-3-2 Misaki Cho, Chiyoda-ku, Tokyo, 1010061 Japan
E-mail: ecis24001@g.nihon-u.ac.jp, li.ke@nihon-u.ac.jp

Abstract

The rapid advancement of Artificial Intelligence (AI) is reshaping the traditional structure of production factors in economics. Rather than functioning solely as a complement to capital or labor, AI is increasingly emerging as a distinct production factor with independent attributes. The paper selects the CES production function as a theoretical model and discusses AI from three aspects: AI as an auxiliary production factor of capital and labor, AI as an independent production factor, and AI as a parameter factor of the production function. Its multiple possible roles not only reshape production functions and industrial structures, driving productivity and economic growth, but may also exacerbate industrial imbalances and labor market polarization, carrying profound implications for policy-making and corporate strategy.

Key Words: Artificial intelligence (AI), Production factor, CES production function, Enterprise production, Production structure

1 Introduction

In economics, capital and labor are the most basic production factors in the production function. The two interact with each other and jointly determine the output level and growth rate of the economy. Different forms of production functions emphasize the role and relationship of capital and labor in the production process. Rationally allocating capital and labor and improving production efficiency are the core tasks to promote economic development. In the modern economy, with the advancement of science and technology, the relationship between capital and labor is also constantly evolving. Artificial intelligence (AI) is the latest wave of automation after electricity, internal combustion engines, and semiconductors [1], promoting efficiency improvement, optimizing resource utilization and accelerating innovation.

Chui et al. pointed out in their report that generative AI will have a significant impact on all industries and sectors. The study found that generative AI has the potential to change the anatomy of work and enhance the capabilities of individual workers by automating some personal activities [2]. Eight months after the launch of ChatGPT, the number of automation-susceptible jobs related to writing and coding decreased by 21% compared to jobs requiring manual skills. In addition, the launch of image generation AI technology led to a 17% reduction in jobs related to image creation [3]. But that paper analyzed the short-term impact of freelance platforms and did not design the entire industry and long-term impact. Zheng et al. and their research showed that technical decision-making in the medical field of AI has played a leading role. They proposed that technical decision-making in the medical field of AI should enhance human decision-making and avoid ignoring ethical needs in the medical field [4]. It can be seen that AI is not just a simple replacement for human physical labor, but has already begun to appear as an agent for decision-making. Therefore, this article considers introducing AI into the production function.

2 Production function based on CES function

The production function is a mathematical expression used in economics to describe the relationship between input factors (such as capital, labor, etc.) and output. It reflects the efficiency of the use of factors in the production process and their contribution to output. The general form is: $Q = f(K, L, M, T)$, where Q represents output, K represents capital, L represents labor, M represents raw materials, and T represents technology. The Cobb-Douglas production function is often used to describe the nature of returns to scale, while the CES production function allows for inconsistent substitution elasticities between capital and labor. The linear production function assumes that production factors are fully complementary and must be invested in a fixed proportion. Considering the general versatility of the industry, this paper selects the more general production function CES production function as the research object. The CES production function is:

$$Y = A(\alpha K^{\rho} + \beta L^{\rho})^{\frac{1}{\rho}} \tag{2.1}$$

Y represents output, A represents the technology level, K represents capital, and L represents labor. α is the allocation coefficient of capital, and β is the allocation coefficient of manpower. ρ is the substitution elasticity parameter, which indicates the substitutability between capital factors and labor factors. When $\rho > 0$, they can be easily substituted, and when $\rho < 0$, they are complementary.

3 AI products must be considered as production factor

The economic impact of AI goes beyond traditional "technological progress". AI is no longer just a part of technology, and affect labor and capital in more and more fields, and can even affect the production process as an independent production factor. M. Puerta et al. studied the multi-dimensional development of humans and AI, and proposed a cooperation framework between humans and AI from five aspects: humans as external tools of AI systems, humans and AI reaching a consensus, asynchronous human-machine collaboration, synchronous human-machine collaboration, and human-machine hybrid intelligence, in order to improve the interactivity and adaptability of AI [5]. With the widespread application of AI, the boundaries of these production factors have gradually blurred. For example, in intelligent manufacturing, autonomous driving, AI customer service, etc., AI's automation capabilities have reduced dependence on traditional manpower and are even gradually replacing human labor. A more precise explanation of how AI brings about productivity improvements is needed, which is the prerequisite of all economic analysis. In the past, capital was mainly reflected in fixed asset investment, and AI, as a digital asset, does not fully meet the definition of traditional capital. With AI driving large-scale data generation, data pricing enables data to be recognized as a digital asset. M. Malieckal et al. categorized data pricing strategies into five types: general pricing, quality-based pricing, query-based pricing, privacy-based pricing, and special cases [6]. By integrating forecasting techniques and technology assessment, it highlights the role of technological tools in shaping pricing frameworks and proposes a pathway for developing scientifically grounded data pricing strategies. AI has strong scalability and can be replicated and used in horizontal and vertical fields to improve production efficiency, while the marginal cost is relatively low. AI can analyze massive amounts of data and make autonomous decisions. For example, in the management of the supply chain or in the order management process, AI can dynamically adjust inventory based on the above digital information, optimize logistics routes, and improve overall operational efficiency. AI can create new business models, such as targeted search engines, personalized recommendation systems, and the emergence of business decisions based on order information. The return of a production factor depends on its contribution to the production function. Incorporating AI into the production function can rationally analyze changes in the income distribution pattern. The impact of AI on different industries varies significantly, with some sectors experiencing significant productivity increases while others experiencing little change. At the policy level, for example in areas such as education, taxation, and industrial subsidies, a clear production function framework is crucial for identifying how AI is changing the contributions of various factors across industries and formulating relevant policies.

4 AI products as production factors in the production function

（1）AI plays a role as a supplementary factor to capital and labor

General-purpose technologies such as AI may both drive substitution and create new tasks [7]. When AI is introduced into the production process, it improves the traditional labor market, mainly in the following aspects: complete substitution, auxiliary role, and creation of new types of jobs. In repetitive, highly predictable tasks, AI can completely replace the existing labor force. For example, the customer service work has been almost completely replaced by AI; the work of ordinary programmers is also gradually being replaced by AI. In other words, AI is equal to labor. Even if some jobs cannot be completely replaced by AI, AI plays the role of an "enhancer" for labor, assisting employees in processing information and improving the efficiency of equipment operation. It can also improve labor efficiency by optimizing processes. It can even help make decisions based on pre-set conditions. At the same time, the participation of AI has also spawned many new professions and positions, such as data scientists, AI engineers, AI ethics experts, etc. Therefore, AI has already affected the production factor of labor in all aspects. Bonfiglioli A et al. used econometric models to show that the adoption of AI can replace some jobs, or supplement some jobs and improve productivity [8]. This means that in some industries, it can completely replace labor. At the same time, in some industries, the improvement of industry productivity increases the total output of the industry, thereby increasing the demand for labor. The adoption of AI has different impacts in different industries.

As a factor affecting labor force participation, the new CES production function formula is obtained as follows:

$$Y = A[\alpha K^{\rho} + \beta(\gamma L + (1-\gamma)AI)^{\rho}]^{\frac{1}{\rho}}, \tag{4.1}$$

At this time, β also becomes the allocation coefficient for the combination factors of labor and AI, where γ is the allocation coefficient for labor under the combination factors.

In fact, there is also substitutability between labor and AI, and if its elastic substitution parameter is set to η_L, then equation (4.1) can be transformed into:

$$Y = A\left[\alpha K^{\rho} + \beta(\gamma L^{\eta_L} + (1-\gamma)AI^{\eta_L})^{\frac{\rho}{\eta_L}}\right]^{\frac{1}{\rho}}. \tag{4.2}$$

When enterprises invest in the above three production factors, they are generally subject to budget constraints. Therefore, the budget constraints are as follows:

$$rK + wL + p_{AI}AI \leq C \tag{4.3}$$

Among them, r represents the price of unit capital, w represents the wage cost of unit labor, and p_{AI} represents the cost of using unit AI service or unit technology.

Use the Lagrangian function to solve and construct the Lagrangian function as follows:

$$\mathcal{L}(K, L, AI, \lambda) = A\left[\alpha K^{\rho} + \beta(\gamma L^{\eta_L} + (1-\gamma)AI^{\eta_L})^{\frac{\rho}{\eta_L}}\right]^{\frac{1}{\rho}} - \lambda(rK + wL + p_{AI}AI - C) \tag{4.4}$$

Assuming $Z = \gamma L^{\eta_L} + (1-\gamma)AI^{\eta_L}$, taking the partial derivative of the K vector to make it equal to 0 gives the following:

$$\partial\mathcal{L}/\partial K = A\left(\alpha K^{\rho} + \beta Z^{\frac{\rho}{\eta_L}}\right)^{\frac{1}{\rho}-1} \cdot \alpha\rho K^{\rho-1} - \lambda r = 0 \quad (4.5)$$

taking the partial derivative of the L vector to make it equal to 0 gives the following:

$$\partial\mathcal{L}/\partial L = A\left(\alpha K^{\rho} + \beta Z^{\frac{\rho}{\eta_L}}\right)^{\frac{1}{\rho}-1} \cdot \beta\frac{\rho}{\eta_L} Z^{\frac{\rho}{\eta_L}-1} \cdot \gamma L^{\eta_L-1} - \lambda w = 0 \quad (4.6)$$

taking the partial derivative of the AI vector to make it equal to 0 gives the following:

$$\partial\mathcal{L}/\partial AI = A\left(\alpha K^{\rho} + \beta Z^{\frac{\rho}{\eta_L}}\right)^{\frac{1}{\rho}-1} \cdot \beta\frac{\rho}{\eta_L} Z^{\frac{\rho}{\eta_L}-1} \cdot (1-\gamma)AI^{\eta_L-1} - \lambda p_{AI} = 0 \quad (4.7)$$

taking the partial derivative of the λ vector to make it equal to 0 gives the following:

$$rK + wL + p_{AI}AI = C \quad (4.8)$$

Dividing equation (4.6) by (4.7) yields:

$$\frac{w}{p_{AI}} = \frac{\gamma}{1-\gamma}\left(\frac{L}{AI}\right)^{\eta_L-1}$$

After deformation, we can get the following:

$$\frac{L}{AI} = \left[\frac{w(1-\gamma)}{p_{AI}\gamma}\right]^{\frac{1}{\eta_L-1}} \quad (4.9)$$

Dividing equation (4.5) by (4.6) yields:

$$\frac{K^{\rho-1}}{L^{\eta_L-1}} = \frac{r}{w}\cdot\frac{\beta\gamma}{\alpha} Z^{\frac{\rho}{\eta_L}-1} \quad (4.10)$$

From formula (4.9), we can see that when AI is used as an auxiliary factor affecting labor, the input ratio is affected by the price of AI p_{AI}. If the price of AI decreases or the marginal output of AI increases, enterprises will definitely increase their investment in AI. In areas where γ is larger, the possibility of AI replacing labor L is greater. From formula (4.10), we can see that the exponential term represents the nonlinear amplification or suppression effect $Z^{\frac{\rho}{\eta_L}-1}$ of the combined factor of labor and AI on marginal returns. The increase in the use of AI may indirectly affect the marginal benefits of capital K. In the capital factor market, the impact and substitution of AI on capital are also obvious. In reality, AI technology is often embedded in machines, equipment or production systems. AI-driven automated equipment, predictive maintenance systems or intelligent manufacturing platforms enable the same amount of capital investment to have higher marginal output. AI can help companies optimize capital allocation, analyze market trends and business performance through big data analysis and machine learning, and make more accurate investment decisions. AI can process a large amount of market data, predict investment returns, and guide the optimal allocation of capital. AI also spawned new forms of capital, such as intelligent capital, virtual capital, and data capital. Tambe P et al. have proposed that digital capital has become a key production factor, accounting for 25% of the total assets of a few star companies, and the value of these companies is still growing, and its growth rate is far greater than that of traditional capital, and it can also predict the future productivity of companies [9]. This situation can be modeled by embedding AI into the production function of the capital item, which means that AI increases the "effective use" of capital, and the new CES production function formula can be obtained as follows:

$$Y = A[\alpha(K + AI)^{\rho} + \beta L^{\rho}]^{\frac{1}{\rho}} \tag{4.11}$$

At this time, α also becomes the allocation coefficient for the combination factors of capital and AI, where γ is the allocation coefficient for capital under the combination factors of capital and AI. Because there is also substitutability between capital and AI, if the elastic substitution parameter is assumed to be η_k, formula (4.11) can be transformed into:

$$Y = A\left[\alpha(\gamma K^{\eta_K} + (1-\gamma)AI^{\eta_K})^{\frac{\rho}{\eta_K}} + \beta L^{\rho}\right]^{\frac{1}{\rho}} \tag{4.12}$$

If AI acts on capital and labor as production factors at the same time, the following production function can be constructed:

$$Y = A[\alpha(K + \phi_K AI)^{\rho} + \beta(L + \phi_L AI)^{\rho}]^{\frac{1}{\rho}} \tag{4.13}$$

In-depth research. Among them, ϕ_K and ϕ_L are the distribution coefficients of AI in the case of the combination of capital and AI, and the combination of labor and AI, respectively.

（2）AI as an independent factor

A single basic AI model, with minimal adaptation, can achieve state-of-the-art performance across a wide range of Natural Language Processing tasks [10]. Through a study of more than 500 Japanese companies, Tatsuru Kikuchi found that the adoption of AI investment significantly increased total factor productivity by 2.4% [11]. Acemoglu, D quantitatively estimated the economic impact of AI using Hulten’s theorem, combined with the AI task-level cost savings 27% provided by experimental research, and ultimately speculated that AI’s TFP growth rate over the next 10 years will be approximately 0.53% - 0.66%, and its impact on GDP will be approximately 0.9% - 1.56% [12]. His shortcoming is that the assumptions at the task level are specific tasks, but in the future, AI’s impact on the industry will be comprehensive. AI can be regarded as a technology that independently affects the production process. It directly improves production efficiency or optimizes product quality mainly through technological innovation, automation, data analysis, intelligent decision support, etc. Its role is usually intangible, virtual and intelligent, and is not directly manifested as traditional physical capital or manual labor, but relies on abstract technical elements such as algorithms, computing power and model optimization. Its core role is to optimize decision-making, improve production efficiency or automate processes through learning and reasoning. AI can simulate or perform certain complex tasks such as image recognition, speech processing, predictive analysis, etc. which are usually not directly replaceable by traditional capital or labor. In many fields such as intelligent manufacturing, autonomous driving, financial technology, and medical care, AI can directly affect the production process and output by replacing labor, automating production, and optimizing decision-making processes. Therefore, formula 2.1 can be rewritten as:

$$Y = A(\alpha K^{\rho} + \beta L^{\rho} + \gamma AI^{\rho})^{\frac{1}{\rho}} \tag{4.14}$$

Where AI stands for artificial intelligence, γ: the distribution coefficient of AI, and ρ: the substitution elasticity parameter, which represents the substitutability between AI and capital and labor. When enterprises invest in the above three production factors, they are generally restricted by the budget condition (4.3). Therefore, the budget constraint is as follows:

$$rK + wL + p_{AI}AI \leq C$$

Among them, r represents the price of unit capital, w represents the wage cost of unit labor, and p_{AI} represents the cost of using unit AI service or unit technology.

Use the Lagrangian function to solve and construct the Lagrangian function as follows:

$$\mathcal{L}(K, L, AI, \lambda) = A(\alpha K^{\rho} + \beta L^{\rho} + \gamma AI^{\rho})^{\frac{1}{\rho}} - \lambda(rK + wL + p_{AI}AI - C) \tag{4.15}$$

Taking the partial derivative of the K vector to make it equal to 0:

$$\partial\mathcal{L}/_{\partial K} = A(\alpha K^{\rho} + \beta L^{\rho} + \gamma AI^{\rho})^{\frac{1}{\rho}-1} \cdot \alpha\rho K^{\rho-1} - \lambda r = 0 \tag{4.16}$$

Taking the partial derivative of the L vector to make it equal to 0:

$$\partial\mathcal{L}/_{\partial L} = A(\alpha K^{\rho} + \beta L^{\rho} + \gamma AI^{\rho})^{\frac{1}{\rho}-1} \cdot \beta\rho L^{\rho-1} - \lambda w = 0 \tag{4.17}$$

Taking the partial derivative of the AI vector to make it equal to 0:

$$\partial\mathcal{L}/_{\partial AI} = A(\alpha K^{\rho} + \beta L^{\rho} + \gamma AI^{\rho})^{\frac{1}{\rho}-1} \cdot \gamma\rho AI^{\rho-1} - \lambda p_{AI} = 0 \tag{4.18}$$

Taking the partial derivative of the λ vector to make it equal to 0:

$$rK + wL + p_{AI}AI = C \tag{4.19}$$

By solving the above equations simultaneously, we can obtain the values of K, L, and AI, which are the amounts of capital, labor, and AI investment respectively under the limited constraint condition C. Dividing equations (4.16) and (4.17) can eliminate the Lagrangian factor,

$$\frac{\alpha\rho K^{\rho-1}}{\beta\rho L^{\rho-1}} = \frac{r}{w}$$

After sorting, the optimal investment ratio can be obtained as follows:

$$\frac{K}{L} = \left(\frac{\beta r}{\alpha w}\right)^{\frac{1}{\rho-1}} \tag{4.20}$$

Similarly, by dividing equations (4.16) and (4.18), and dividing equations (4.17) and (4.18), we can obtain the following input ratio equations:

$$\frac{K}{AI} = \left(\frac{\gamma r}{\alpha p_{AI}}\right)^{\frac{1}{\rho-1}} \tag{4.21}$$

$$\frac{L}{AI} = \left(\frac{\gamma w}{\beta p_{AI}}\right)^{\frac{1}{\rho-1}} \tag{4.22}$$

Substituting (4.21) and (4.22) into (4.3),

$$rAI\left(\frac{\gamma r}{\alpha p_{AI}}\right)^{\frac{1}{\rho-1}} + wAI\left(\frac{\gamma w}{\beta p_{AI}}\right)^{\frac{1}{\rho-1}} + p_{AI}AI = C$$

The AI can be obtained as

$$AI = C/\left[r\left(\frac{\gamma r}{\alpha p_{AI}}\right)^{\frac{1}{\rho-1}} + w\left(\frac{\gamma w}{\beta p_{AI}}\right)^{\frac{1}{\rho-1}} + p_{AI}\right] \tag{4.23}$$

Similarly, L and K can be obtained as follows:

$$K = C/\left[r + w\left(\frac{\beta r}{\alpha w}\right)^{\rho-1} + p_{AI}\left(\frac{\gamma r}{\alpha p_{AI}}\right)^{\rho-1}\right] \tag{4.24}$$

$$L = C/\left[r\left(\frac{\beta r}{\alpha w}\right)^{\frac{1}{\rho-1}} + w + p_{AI}\left(\frac{\gamma w}{\beta p_{AI}}\right)^{\rho-1}\right] \tag{4.25}$$

From equations (4.23), (4.24), and (4.25), we can see that the marginal output of each factor is only related to its own quantity and price. As long as the marginal cost ratio of any two factors is known, it can help the enterprise decide its input amount. In summary, if AI acts as both an auxiliary factor and an independent factor, the production function can be changed to:

$$Y = A(\alpha(K + \phi_K AI)^\rho + \beta(L + \phi_L AI)^\rho + \gamma AI^\rho)^{\frac{1}{\rho}} \tag{4.26}$$

Among them, ϕ_K and ϕ_L are the distribution coefficients of AI in the case of the combination of capital and AI, and the combination of labor and AI, respectively.

(3) AI as a parameter factor affects the substitutability between capital and labor

AI innovations can bring about changes in employment [13]. AI is a systemic strategic issue that is closely related to organizational structure and decision-making processes [14]. AI adoption also directly affects the substitution relationship between capital and labor in enterprises. In this case, assuming that $\rho = \rho(AI)$ in equation (2.1), the production function is as follows:

$$Y = A\left[\alpha K^{\rho(AI)} + \beta L^{\rho(AI)}\right]^{\frac{1}{\rho(AI)}} \tag{4.27}$$

The budget constraint in this case is:

$$rK + wL + \leq C \tag{4.28}$$

The solution to the Lagrange equation is:

$$\frac{K}{L} = \left(\frac{\beta r}{\alpha w}\right)^{\frac{1}{\rho(AI)-1}}. \tag{4.29}$$

As can be seen from formula (4.29), AI can affect the input structure between labor and capital. The more powerful AI is, the more companies tend to use capital to replace workers when facing rising labor costs.

5 Conclusion

Studying and managing AI as a production factor, or an auxiliary factor that affects capital and labor, or a substitution factor between capital and labor, will not only help formulate reasonable economic policies, but also promote enterprises to use AI resources more efficiently and improve overall economic benefits. AI, as an auxiliary factor to enhance capital and labor, helps to understand the role of AI in different industries, but may aggravate the imbalance between industries. AI as an independent production factor helps to deepen the understanding of the modern economic system, because the reconstruction of the production function may lead to unprecedented structural changes in some industries, and there may be "winner-takes-all" platform-type enterprises, providing a reference for policy formulation and corporate strategic planning. AI, as a substitution parameter between capital and labor, may determine whether it is "capital-biased" or "labor-biased" according to the characteristics of the industry. Different paths will cause major changes in institutions within the industry, and may also lead to polarization of workers in some industries, or create new types of jobs. The status of AI in the modern economic system has far exceeded that of traditional production tools, and its impact on productivity, economic growth, industrial structure and labor market is far-reaching.

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Corresponding Author: Wei SHE

Graduate School of Economics, Nihon University

1-3-2 Misaki Cho, Chiyoda-ku, Tokyo 1010061, Japan

E-mail: ecis24001@g.nihon-u.ac.jp