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Research on the Productivity Paradox of Information Technology

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Abstract: The rapid development of new-generation information technology, such as the internet, big data, and artificial intelligence, has shifted the focus of theoretical and commercial attention on whether information technology can increase productivity growth. This paper systematically combs the evolution trend of the productivity paradox of information technology from the macro and micro levels. The findings revealed that there are still no unified conclusions at the macro-level, but it is generally believed that there is no productivity paradox at the micro level. There are some differences between developed and non-developed countries as well as across different industries. Based on the complementary mechanism theory, it is found that information technology forms a complementary effect with human capital, technological innovation, organizational change, and management practice, which can provide ideas for solving the productivity paradox of information technology. Finally, the future research direction for the productivity paradox of information technology is determined from the macro and micro levels.

Keywords: Information technology; Digital technology; Productivity paradox; Solow paradox; Research progress

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1. Introduction

In recent years, the new generation of information and communications technology represented by the internet, big data, and artificial intelligence has advanced by leaps and bounds, profoundly changing human production and life, as well as becoming highly influential new technologies. Germany, Japan, and other advanced manufacturing countries have successively promoted the application of digital technology represented by artificial intelligence, industrial internet, and big data in the manufacturing industry to a strategic height, in order to enhance the competitiveness of the manufacturing industry. However, there has long been a debate in academia about whether information technology can improve productivity.

In 1987, Solow, the Nobel Laureate in economics, put forward the famous "Information Technology Productivity Paradox": "You can see the computer age everywhere except in the productivity statistics [1]," which is also known as "Solow Paradox" or "Productivity Paradox." Subsequently, some theoretical explanations, such as the Statistical Mismeasurement Hypothesis and Time Lag Hypothesis, believe that there is no paradox, whereas the Capital Stock Hypothesis and Substitution Effect Hypothesis believe that there is a paradox, but there is still no clear and unified theoretical explanation. As a new generation of information and communications technology, digital technology is also involved in the controversy of productivity paradox. The impact of digital technology, such as artificial intelligence, on productivity is actually a continuation of the discussion on the productivity paradox of information technology. The

existing literature on the productivity paradox of information technology is mainly divided into macro and micro levels.

2. Macro level

According to the data of the U.S. Bureau of Labor Statistics, from 1973 to 1997, the average annual growth rates of labor productivity and total factor productivity in the non-agricultural production sector were 1.1% and 0.2%, respectively, both lower than the 2.9% and 1.9% from 1949 to 1973. At first, it was theoretically believed that the reasons for the slowdown of economic growth might be the external shocks, such as the two oil shocks, inflation, and high taxes in the 1970s, which were not associated with the revolution of information technology. Scholars discovered, however, that while these external shocks had dissipated or lessened in subsequent years, the tendency of economic growth slowing had not [2]. It was not until Solow put forward the "Information Technology Productivity Paradox" in 1987 that the theoretical realm realized that the time when economic growth began to slow down coincided with the time when the information technology revolution began. Consequently, there were a large number of theoretical articles on the productivity paradox of information technology.

From a theoretical point of view, there is still no clear theoretical explanation for the productivity paradox of information technology. Jiang and other researchers divided the existing explanations into optimism and pessimism [2]. Among them, optimism is represented by the Statistical Mismeasurement Hypothesis and Time Lag Hypothesis. They acknowledged that information technology can promote economic growth, but it is not reflected at present for some reasons. Pessimism is represented by the Capital Stock Hypothesis and Substitution Effect Hypothesis. Based on the analysis of the traditional neoclassical economic growth theory, it is believed that the role of information technology in promoting economic growth is not that effective. The Statistical Mismeasurement Hypothesis claims that traditional GDP statistical methods cannot accurately calculate the real GDP growth of service industries, such as trade, insurance, and finance, despite the fact that the economic structure of the United States is dominated by the service industry, resulting in large errors in the overall GDP, and the degree of mismeasurement is even more prominent under the information technology revolution [3]. The Time Lag Hypothesis holds that there is a certain time lag in the role of information technology in promoting economic growth, which may be attributable to the adjustment time lag in the system or management mode, the proficiency of workers in information technology, and the lack of computer standardization [4]. The Capital Stock Hypothesis considers that the proportion of information technology capital is still very small statistically; from the perspective of economic growth accounting theory, the contribution of information technology capital to economic growth is limited [5]. The Substitution Effect Hypothesis argues that the relative price changes across various types of capital as well as between capital and labor will produce a substitution effect [6]. When the price of information technology capital is high, the substitution effect on other capital and labor factors is small, but with the decrease in the price of information technology capital, the substitution effect becomes larger, and the contribution of information technology capital will gradually increase. In addition, the Mismanagement Hypothesis represented by Brynjolfsson and Hitt holds that the poor management of enterprises leads to continuous and inefficient investment in information technology, which does not give full play to the potential value of information technology [7].

From an empirical point of view, there is still no unified conclusion at the macro level. In the early 1990s, most scholars believed that the productivity paradox of information technology existed. In 1991, Roach found that more than 85% of the U.S. service industry was using information technology, but productivity still did not improve [8]. Based on the economic growth accounting theory, Oliner and Sichel thought that computers contributed very little to economic growth from 1970 to 1992 because depreciation offset most of the gains of computers [5]. After 1995, the U.S. economy began to recover; BusinessWeek

called it the New Economy. During this period, the research that suggested the existence of information technology productivity paradox mainly came from Roach [9], Gordon [10], and others, whereas the conventional view believed that information technology could promote the economy. Solow claimed that productivity paradox had dissipated in 2000. In that year, Oliner and Sichel re-examined the contribution of computers to the U.S. economic growth and found that the contribution of information technology progressed and its application to productivity increased significantly in the second half of the 1990s [11].

After the Internet bubble burst in the early twenty-first century, the information technology industry entered a period of adjustment. At the same time, the rapid development of the new generation of information and communications technology has triggered a controversy over the productivity paradox of information technology. Van Ark combed relevant literature on the productivity paradox of information technology in the era of digital economy and found that despite the rapid development of digital technology, such as the internet and cloud computing, digital economy is still in the installation phase, and the exertion of productivity effect requires digital technology to launch into the deployment phase [12]. Based on the fourth industrial revolution, Saniee and other researchers predicted that the second productivity jump in the United States would occur from 2028 to 2033, and the total penetration rate of digital technology would reach the critical point of 51% [13].

3. Micro level

Although the productivity paradox of information technology originated from the macro level, the research at the micro level is equally beneficial to determining the causes of this productivity paradox. According to Brynjolfsson, the productivity paradox of information technology may be caused by the lag in the realization of information technology investment, poor management of technology investment, and redistribution of profits in the market or economy, resulting in the weight of information technology at the firm level, but not at the macro level [14]. Pilat and Criscuolo suggested that the productivity paradox at the macro level is due to the differences in information technology across enterprises and the unbalanced absorption as well as diffusion of information technology in the economy [15]. It can be seen that the research at the macro level cannot explain the heterogeneity of information technology investment and utilization of different enterprises [16], whereas the research at the micro level can better gauge the diffusion effect of information technology, especially in reflecting the quality changes brought by information technology [17], so as to find a way to solve the productivity paradox.

The early researches of productivity paradox vary at the micro level, but a series of studies represented by Brynjolfsson and Hitt suggested that the productivity paradox at the firm level dissipated after 1991 [7]. However, with the emergence of digital technology, such as artificial intelligence, Brynjolfsson and other researchers claimed that a “modern productivity paradox” is gradually emerging, in which digital technology and productivity show a positive “J-shaped” curve [18,19]. According to Gordon [20], the achievements of the third industrial revolution will be difficult to surpass in the next 40 years. It is expected that industrial robots will not completely replace human labor in the next few decades. Technologies such as 3D printing and big data are not mature enough and have a limited impact on enterprises. Acemoglu and several other researchers found that in IT-intensive industries, labor productivity has increased to a certain extent, mainly because the reduction of the labor force is greater than that of output, and it is too early to judge whether Solow Paradox has disappeared [21]. According to Acemoglu and Restrepo [22], the excessive use of digital technology, such as artificial intelligence, may lead to improper allocation of capital and labor, thus hindering the improvement of enterprise productivity. However, Purdy and Daugherty claimed that artificial intelligence, as a new factor of production, can improve enterprise productivity through three ways: intelligent automation, labor skills and material capital improvement, and technological innovation [23]. It has been found in a study that the application of digital technology can significantly promote enterprise

productivity by using the enterprise data of 22 industries in 20 OECD countries from 2010 to 2015 [24].

4. Regional and industrial differences

4.1. Regional differences

Some studies have shown that the productivity paradox of information technology has certain national differences. Timmer and other researchers compared the productivity effects of information technology in Europe and the United States from 1995 to 2001, and found that during the sample period, the deepening of information technology capital and the improvement of total factor productivity in the United States were significantly higher than those in European countries [25]. Based on a survey of nearly 1,000 manufacturing enterprises in two major developing countries – Brazil and India – in 2005 [26], it was found that ICT has a significant role in promoting the productivity of those countries. Myovella and several other researchers compared the impact of digitization on the economic growth of 41 countries in sub-Saharan Africa and 33 OECD countries from 2006 to 2016; they found that digitization has a significant positive impact on the economic growth of both developed and underdeveloped countries, but compared with OECD countries, broadband internet has the least impact on sub-Saharan African countries, while mobile communication has a greater impact on sub-Saharan African countries compared to OECD countries [27]. According to the production theory, Gan and Zhang established a two-equation stochastic frontier model based on the transcendental logarithmic production function and compared the production efficiency of information technology in developed and developing countries from 1996 to 2012; they found that information technology capital reduces the production efficiency of developed countries and improves the production efficiency of developing countries [28]. Based on the local dynamic adjustment model, Wei compared the impact of ICT on the economic growth of 13 countries from 2001 to 2016 and found that ICT has a significant positive impact on the economic growth of both developed and developing countries, and that the digital divide between developed and developing countries has gradually narrowed [29].

In addition to the differences between developed and developing countries, the productivity paradox of information technology differs in different regions in the same country. Kireyeva and other researchers studied the impact of ICT on the economic growth in the high, medium, and low development regions of Kazakhstan, and found that the implementation and development speed of ICT vary from region to region; the number of internet users in the least developed regions still lags, but ICT has a significant positive impact on the economic growth of all regions [30]. Based on the data of the Russian Federation from 2010 to 2016, Dementiev divided Russia into two groups: the productivity paradox group (productivity decreased significantly) and non-productivity paradox group (productivity did not decline or the decline was small); he found that the productivity paradox was caused by the steadily depleted reserves to upgrade previously mastered technology and to divert the resources of existing products to reconstruction or research and development (R&D) [31]. Based on the survey data on Chinese enterprises conducted by the world bank in 2012, the complementary effects of information technology and labor force in regions with high and low marketization processes in China were compared; it was found that the complementary effects of information technology and highly skilled labor force are stronger in regions with high marketization process, but the impact of the market-oriented process on the complementary effect of information technology and long-term employed labor force is not significant [32]. Based on China's inter-provincial data from 2003 to 2015, Li and other researchers investigated the impact of intelligence on the total factor productivity of the manufacturing sector in relation to regional differences; they found that intelligence has a significant role in promoting the total factor productivity of the manufacturing sector in the central and western regions, with a greater role in the western region, but no significant role in the eastern region.

4.2. Industrial differences

The productivity paradox of information technology varies in different industries. The existing studies generally believe that there is no information technology productivity paradox in the manufacturing industry [34], while the results in the service industry are inconclusive. In 1967, American Economist Baumol proposed that the productivity improvement in the service sector may be less than that in the commodity production sector, which is known as "Baumol's cost disease." Roach found that the productivity effect of information technology in the United States is much higher in the manufacturing industry than in the service industry, and there may be inefficiency caused by over-investment in the service industry [8]. Using the data of the American service industry from 1977 to 1995, Triplett and Bosworth found that with the increase of information technology capital, the productivity of the American service industry is accelerating, and Baumol's cost disease no longer exists [35]. Sun and Liu examined China's industry panel data from 1979 to 2014 and discovered that information technology plays a role in promoting the total factor productivity of the culture, education, and financial industries, but it has a relatively small role in promoting the real estate industry [36].

In the financial service industry, the use of big data analysis tools to improve bank production efficiency was analyzed based on a case of a commercial bank in Asia; it was found that big data analysis helps to improve the marketing and risk management performance of commercial banks, along with its production efficiency [37].

In the public service industry, based on the panel data of American police departments from 1987 to 2003, Garicano and Heaton found that the application of information technology has no significant relationship with the reduction of crime rate, the increase of case closure rate, and other productivity indicators, whereas the information technology that increases the crime reporting rate leads to a decline in productivity [38].

In the pharmaceutical industry, Miller and Tucker found that healthcare information technology can significantly reduce the mortality of newborns in the United States and save about $531,000 per newborn; this is mainly due to the use of electronic medical records and expert systems to improve medical efficiency [39]. Liu and other researchers pioneered the use of big data in medicine, with specific application to tumors, neuropsychiatric disorders, and cardiovascular diseases [40]. Countries all over the world have begun to establish their own gene bank. Analyzing diseases at the gene level leads to more beneficial and efficient treatment than traditional treatment methods.

In the construction industry, Triplett and Bosworth found that information technology has a positive productivity effect in trade and financial industries, whereas it has an opposite effect in education and construction industries [41]. However, a different study found that digital technology has a positive impact on the productivity of the German construction industry based on three case studies: robot, 3D printing, and BIM software [42].

5. Solving the productivity paradox of information technology

Milgrom and Robert first proposed the complementary mechanism theory of information technology in 1990 and systematically demonstrated the complementarity among information technology, human capital, and organizational change [43]. The complementary mechanism theory holds that in addition to the contribution of factors to productivity, the mutual empowerment between factors will also improve enterprise productivity. The complementarity between elements is the complementary effect. With the complementary effect, increasing the input of one element will increase the return of another element [44]. According to Tanriverdi and Venkatraman [45], complementary resources are interdependent. When enterprises develop a set of complementary related resources in their business departments at the same time, the firm performance will be improved. Jeffers and several other researchers believe that information

technology resources and non-information technology resources are complementary, which can improve the core competence of enterprises and their performance [46]. According to several researchers [47], complementarity includes the concept of synergy and systematic effect, in which the whole is greater than the sum of parts. When two substances are complementary, their potential to create value will be greatly improved. Competitors find it difficult to replicate and copy complementary resources and competencies.
The complementary mechanism theory provides a new research idea for the productivity paradox of information technology at the micro level. Scholars have begun to pay attention to the relationship between information technology and organizational variables. Although researchers at the micro level believe that there is no productivity paradox of information technology, there are still great differences in the return of information technology investment in different enterprises [48]. Previous studies have shown that information technology is complementary to human capital, innovation investment, organization change, and management practice. It has been found that information technology promotes productivity at the firm level and shows no significant difference between the United States and European countries; moreover, ICT, as a general technology, can further promote innovation [49]. Bloom and other researchers believe that the complementarity between organization management and information technology is conducive to improving enterprise productivity [50]. Based on a questionnaire on China's industrial enterprises, distributed by the World Bank in 2005 [32], it was found that there is no information technology productivity paradox in China's manufacturing, and high-skilled workers and long-term workers can improve the promotion effect of ICT on productivity.

6. Conclusion and prospects

The productivity paradox of information technology was first proposed at the macro level. Due to the lag of income realization of information technology investment, poor management of technology investment, and redistribution of profits in the market or economy, information technology was found to have a positive effect at the micro level. The productivity paradox of information technology has some differences between developed and non-developed countries as well as across different industries. At present, the results are inconclusive at the macro level, whereas most studies have claimed that there is no information technology productivity paradox at the micro level. The complementary mechanism theory provides a new research idea for the productivity paradox of information technology at the micro level. It has been discovered that information technology forms a complementary effect with human capital, technological innovation, organizational change, and management practice, which can significantly enhance the promotion of information technology on productivity at the micro level.

With the rapid development of digital technology, the research on information technology productivity paradox mainly focuses on the productivity paradox of digital technology in the future. The challenge lies in the measurement of digital technology and the impact mechanism of digital technology on productivity. At the macro level, the impact mechanism of digital technology on macro productivity can be studied by establishing regional digitization through a series of indicators, such as digital technology infrastructure, investment, and application. At the micro level, the digitization of enterprises can be measured by making statistics of word frequency related to digital technology in the annual report of enterprises through Python software. There is research on how to enhance the productivity effect of information technology through the complementary mechanism, but none about how information technology affects enterprise productivity. We may investigate how information technology, particularly digital technology, influences company productivity in the future. The study of these issues will aid in understanding the mechanism by which information technology affects productivity, as well as in improving the productivity effect of information technology, and avoiding the negative impact of information technology.

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