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How ICT and R&D affect productivity? Firm level evidence for China

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ABSTRACT

Based on an extended three-step CDM model, this paper addresses the impacts of research and development (R&D) and information and communication technology (ICT) on firm productivity for the World Bank innovation survey data of China. The study includes ICT investment and R&D as the two main inputs into innovation and productivity. We find that R&D and ICT investments positively affect product innovation and process innovation, with R&D being more important for innovation and productivity, and ICT being more important for innovation and no direct effect on productivity. We conclude that R&D and ICT investments increase the probability of product innovation and process innovation, which increase firm's productivity, suggesting that R&D and ICT investments indirectly affect productivity through innovation.

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1. Introduction

Labor productivity is highly correlated with economic growth and a key indicator of a country's future development. With China's economy entering a 'new normal', China urgently aspires to get out of the 'middle income trap '. However, its traditional growth, driven by capital and low labor costs, is unsustainable. As such, increasing productivity becomes the key to unlocking China's economic potential (Wang, 2017).

Although Solow (1987) proposed the famous productivity paradox that 'the IT industry is everywhere, and its contribution to productivity is minimal', there has been debate about whether information and communication technology (ICT) contributes to labor productivity. For example, Acemoglu et al. (2014) presented new evidence, which makes people doubt whether there is a positive correlation between ICT and productivity in the United States. However, in general, microeconomic evidence from some countries, especially developed ones, suggests that ICT may be an

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important driver of productivity (Alvarez et al., 2010; Brynjolfson et al., 2002; Cardona et al., 2013; Hall et al., 2013).

ICT is an inclusive term, covering all communication equipment or application software and various related services and application software. And ICT is widespread in developed countries and is becoming increasingly important for developing countries. While the application of ICT is still evolving, it has become one of the most important drivers of global economic growth and has a significant impact on improving firm profits, productivity, and social employment. Nowadays, global economies generally regard accelerating information technology innovation and maximizing the release of digital dividends as key strategies to deal with the instability and uncertainty of growth, deepen structural reforms, and promote sustainable development in the 'post-financial crisis' era. Informatization, which signifies new directions and new ways to achieve productivity, has become a leading force in innovation and transformation, with ICT as one of the potential drivers of productivity growth.

Research and development (R&D) refers to systematic and creative activities in the field of science and technology that increase knowledge and the use of such knowledge to create new applications. Increased R&D investment stimulates investments and thus, increases total factor productivity (TFP) (Griliches, 1979). R&D expenditure also plays a significant, positive role in labor productivity (Harhoff, 1998). In recent years, more international scholars have focused on the impacts of R&D and ICT investments on firm innovation and productivity (Cette et al., 2017; Hall et al., 2013; Polder et al., 2009). However, there are few studies on the impact of R&D and ICT on productivity at the same time, especially in China. This study supplements existing literature and provides some reference for Chinese firms to carry out R&D and ICT investment strategies. The structure of the rest of this paper is as follows: the first part is literature review, the second part is the extend model of Crépon, Duguet and Mairesse (CDM) with R&D and ICT as input factor, followed by data description and empirical analysis, and the last part summarizes the whole paper.

2. Literature review

2.1 R&D and Productivity

Economic theory (Romer, 1989; Solow, 1957) points out that technological advancement is the main source of long-term productivity growth. Schumpeter (1934) put forward the idea in the early 20th century that 'innovative behavior is the core factor of firm competitiveness and dynamic efficiency', while the empirical studies of Minasian (1962), Minasian (1969), and Griliches (1964) also showed that R&D is an important factor in improving productivity. Griliches (1979) creatively proposed a theoretical model of the knowledge production function and regarded the innovation output as a function of R&D input, finally concluding that productivity growth would be related to the R&D if measured correctly to some extent. Scholars have carried out abundant empirical analyses on the relationship between R&D input and firms productivity, and most studies have shown that the R&D has a significant effect on firms' productivity. At the same time, by using 2002 data of China's manufacturing industry, Wu (2006) concluded that the R&D input has a significant contribution to productivity. Sun and Wang (2014) found that the productivity level of enterprises with R&D is 21.5% higher than that of enterprises without R&D using the propensity score matching method (PSM). Liu and Hou (2014) used data of 671 firms from the records of the Haidian District of Beijing to examine how different types of R&D expenditure (of varied industries and ownership structures) affect enterprise productivity, the results showed that R&D investment has a significant positive impact on enterprise productivity, but the R&D output elasticity coefficients of various firms differ by type: private, state-owned, or foreign-funded.

2.2. ICT and productivity

In the past few years, substantial attention has been paid to the impact of ICT on economic growth and firm performance (Oecd, 2004). With ICT as the contemporary high-tech, it is generally believed that the application of ICT can reduce the transaction cost of firms, promote organizational efficiency, and improve product quality and customer satisfaction, thereby improving the profitability of firms' progress. Some economists have also tried to study the impact of ICT on productivity.

The earliest research on the relationship between ICT and productivity was mainly to explain the so-called "Solow Paradox," which conveys that there is nowhere to see computers except in productivity statistics (Solow, 1987). How to correctly measure the effect of ICT on productivity at the micro level is a complex issue. Many of the early ICT literature, mainly in the 1980s and early 1990s, believed that the relationship between ICT and firm productivity is weak or unrelated (Margetts & Willcocks, 1993; Roach, 1987; Strassmann, 1985; Wilson, 1995). Harrison (1996) pointed out that investing in IT alone, without regard to other factors, does not increase productivity. Some scholars argued that the impact of ICT investment on productivity is difficult to determine, and that ICT may be conducive or unfavorable to enhancing productivity (Weill & Olson, 1989). Engelbrecht and Xayavong (2006) stated that there is a certain sensitivity difference between ICT and productivity at different time periods. Han et al. (2017) found that the influence of the informatization on productivity exhibits dynamic stages, with the characteristics of early decline and later rise.

Nowadays more and more scholars consider that informatization is conducive to enhancing productivity. Oliner and Sichel (2000) believed that in the 1990s, the core cause of productivity and economic growth in the United States was the application of information technology. Colecchia et al. (2002) found that the contribution of capital accumulation of information technology to economic growth was 2% and 5% in the 1970s and 1980s respectively, which changed to between 3% and 9% in the 1990s. Moreover, Milgrom and Roberts (1990) found that investments in information improve firms' productivity by reducing costs (direct impact) and inducing innovation (indirect impact). Since the 21st century, some scholars, through empirical research, have also supported the view that improvements in informatization level can effectively increase productivity. For example, the empirical evidence of Bresnahan et al. (2002) suggested that ICT and organizational design play an active role in increasing enterprise productivity. At the same time, Jorgenson (2001) and Shao and Lin (2001) confirmed the existence of excess income attributable to the information level improvement. In China, Wang et al. (2006) and Li and Wu (2008) confirmed that enterprise informatization can improve the production efficiency of firms. The former discovered that the mechanism of enterprise informatization has stage characteristics; the latter confirmed excess profitability attributable to information technology. These results are consistent with the conclusions of Jorgenson (2001) and Shao and Lin (2001).

Some scholars have also studied the complementary effects of ICT and other firm characteristics. For example, Black and Lynch (2001) and Bresnahan et al. (2002) analyzed the interaction between ICT, human capital, and organizational change. However, high-tech enterprises often have a high level of information technology, and enterprises need to have basic knowledge reserve in the use of information technology. This shows that enterprises with higher R&D level can improve productivity more after adopting information technology. But at present, there are few literatures about the impact of information technology and R&D on productivity.

Therefore, this paper takes ICT and R&D as production input factors, and analyzes their impact on productivity by using the extended CDM model. Specifically, this study examines the relationships among R&D and ICT innovation inputs, product innovation, process innovation, and enterprise productivity.

3. Extended CDM model

To explore the effects of ICT and R&D on productivity, this study draws on the research of Polder et al. (2009), Hall et al. (2013), and Álvarez (2016), and extends the model of Crépon et al. (CDM, 1998) to form a three-stage CDM model .

3.1. R&D and ICT Input Equations

In the first phase, we model the decisions of enterprise R&D investments, like the standard CDM model. First, the firm decides whether to start investing in R&D, and if it decides to invest, there must be investment intensity. Based on the CDM model, we use the probit equation. The definition of model selection is as follows:

$$DR_{\mathrm{i}} = \begin{cases} 1, DR_i^* = w_i\alpha + \varepsilon_i > \bar{c} \\ 0, DR_i^* = w_i\alpha + \varepsilon_i \leq \bar{c} \end{cases} \tag{1}$$

Where R represents R&D input and DR_{i} is an observable indicator function. If company i has carried out R&D investment, then the value is 1; otherwise, its value is 0. DR_i^* is a latent variable whereby company i decides to invest in R&D if it is above a given threshold, and ε_i is an error term.w_i is the explanatory vector that affects R&D decisions; and$w_i = (k, SIZE, \mathrm{EXP}, FT, STD, NEI, AGE, EDU)$, $k, SIZE$, EXP represent capital intensity (logarithm of capital per capita), company size (logarithm of number of employees), export respectively; FT, STD, NEI denote the use of foreign technologies, the standardization of the company, and the investment in new equipment, respectively, which are the driving factors of technology; AGE and EDU are company characteristics representing the company's age and labor quality, respectively.

For companies with R&D activities, the corresponding R&D input intensity is calculated as follows:

$$R_{\mathrm{i}} = \begin{cases} R_i^* = z_i\beta + e_i, DR_{\mathrm{i}} = 1 \\ 0, DR_{\mathrm{i}} = 0 \end{cases} \tag{2}$$

Where R_i^* is an unobserved latent variable corresponding to the firm's R&D investment. We use the logarithm of per capita R&D expenditure as the R&D input intensity and use it as a substitute variable for the latent variable. z_i is the determinant vector of the R&D input intensity; $z_i = (SIZE, \mathrm{EXP}, FT, STD, NEI, AGE, EDU)$, and the meaning of each explanatory variable in vector z_i is the same as in vector w_i.

It is assumed that error terms in equations (1) and (2) follow the binary normal distribution with a mean of zero, and its covariance matrix is given by:

$$\begin{pmatrix} 1\rho\sigma_\varepsilon \\ \rho\sigma_\varepsilon\sigma_\varepsilon^2 \end{pmatrix} \tag{3}$$

Similar to the decision equation and intensity equation of the R&D input, we set up the decision equation and the intensity equation of ICT investment. I is represented as ICT investment, and the specific probit equation is as follows:

$$DI_{\mathrm{i}} = \begin{cases} 1, DI_i^* = w_{ICTi}\alpha + \varepsilon_{ICTi} > \overline{c_{ICT}} \\ 0, DI_i^* = w_{ICTi}\alpha + \varepsilon_{ICTi} \leq \overline{c_{ICT}} \end{cases} \tag{4}$$

Where DI_{i} is an observable indicator variable; DI_i^* is a latent variable; and ε_{ICTi} is an error term. w_{ICTi} is a set of explanatory variables that influence ICT investment decisions, $w_{ICTi} = (k, SIZE, \mathrm{EXP}, FT, STD, NEI, AGE, EDU)$.

The ICT input intensity equation is equal to:

$$I_{\mathrm{i}} = \begin{cases} I_i^* = z_{ICTi}\beta + e_{ICTi}, DI_{\mathrm{i}} = 1 \\ 0, DI_{\mathrm{i}} = 0 \end{cases} \tag{5}$$

Where I_i^* is an unobserved latent variable corresponding to the company's ICT investment; z_{ICTi} is an explanatory variable vector of the ICT input intensity, and$z_{ICTi} = (SIZE, \mathrm{EXP}, FT, STD, NEI, AGE, EDU)$.

In addition, we assume that the error terms in the ICT investment decision equation (4) and the ICT input intensity equation (5) follow the binary normal distribution with a mean of zero.

3.2. Innovation output equation

For firms, the main forms of innovation can be divided into technological and non-technological innovation. Using the World Bank's enterprise survey data on China, our model selects two forms of technological innovation: product innovation (*PD*) and process innovation (*PCS*), and takes the sales brought by product innovation and the sales brought by process innovation as the innovation output. The two innovation output equations are as follows. The values of product innovation output (*PDI*) and process innovation output (*PCSI*) are the logarithm values of their innovation outputs.

$$PDI_i = \delta_1 RDI_i^* + \phi_1 ICTI_i^* + \prod\nolimits_1 \xi_i + \varepsilon_{1i} \tag{6}$$

$$PCSI_i = \delta_2 RDI_i^* + \phi_2 ICTI_i^* + \prod\nolimits_2 \xi_i + \varepsilon_{2i} \tag{7}$$

Where RDI^* is the predicted value of R&D investment (expressed by the logarithm of per capita R&D investment); $ICTI^*$ is the predicted value of the enterprise's ICT investment (expressed by the logarithm of the per capita ICT investment), and ξ_i is the explanatory vector that is defined as $\xi_i = (SIZE, \mathrm{EXP}, FT, STD, NEI, AGE, EDU)$.

In the literature, the number of patents or the output value of new products are generally selected as the innovation output, while this study divides the innovation output into product innovation output and process innovation output according to the innovation form, the two outputs are influenced by R&D and ICT investment intensity, as well as other factors, such as environmental and company characteristics.

Existing literature generally believe that innovation output is influenced by innovation input and demand-driven and technology-driven factors. Equations (6) and (7) also incorporate these factors into the equations. The demand factor is expressed by the enterprise export. When an enterprise conducts exports (including direct and indirect exports), its value is 1; otherwise, it is 0. The technology-driven factors are divided into three types based on whether the enterprise 1) uses foreign technology, 2) has internationally certified quality standards, and 3) invests in new equipment. These factors also reflect the innovation ability and innovation quality of the enterprise. The explanatory variables also take into account the size and age of the enterprise. Moreover, the cities in which the enterprise is located and the industry it belongs to are also considered as control variables.

3.3. The labor productivity equation

One of the purposes of enterprise innovation activities is to improve labor productivity and win greater profits, in order to reflect the impact of enterprise innovation activities on labor productivity. We use a Cobb-Douglas production function that includes labor, capital, and intellectual input to derive the labor productivity equation:

$$Y_i = AK_i^{\pi_1} L_i^{\pi_2} INNO_i^{\pi_3} \tag{8}$$

Y is sales; K is capital input; L is the number of workers; and $INNO$ is the innovation output. The following formula can be obtained by transforming formula (8):

$$Y_i/L_i = (AK_i^{\pi_1} L_i^{\pi_2} INNO_i^{\pi_3}/L_i) * (L_i^{\pi_1}/L_i^{\pi_1}) \tag{9}$$

The two sides of the equation (9) are further logarithmic processed. The formula, after sorting out, is obtained as shown in (10).

$$\ln\left(Y_i/L_i\right) = \ln A + \pi_1 \ln\left(K_i/L_i\right) + (\pi_1 + \pi_2 - 1)\ln L_i + \pi_3 \ln INNO_i \tag{10}$$

Finally, the labor productivity equation can be obtained based on formula (10):

$$y_i = a + \pi_1 k_i + \psi SIZE + INNO_i^{*}\pi_3 \tag{11}$$

Where y is the labor productivity (logarithm of per capita sales); k is the logarithm of per capita capital; *SIZE* is the size of the enterprise (logarithm of the number of employees); and $INNO^*$ is the predicted value of the innovation output (expressed by two types of innovation output: product innovation and process innovation).

4. Data description and description statistics

4.1. Data sources and variable selection

The raw data of this study are from the World Bank's survey on China (the latest survey data is from 2012), comprising 2,700 private companies and 148 state-owned firms. The survey scope is evenly distributed in 28 industries such as manufacturing and service industries.

The World Bank's enterprise questionnaire has special questions about innovation and technology. The R&D-related questions are as follows. (1) Regarding R&D activities within the enterprise: Does the company engage in R&D activities within the company? If the activity is carried out, what is the corresponding R&D expenditure? (2) Regarding R&D activities outside the enterprise: Does the company have an agreement with other companies on R&D activities? If there are related activities, what is the corresponding R&D expenditure?

The ICT-related issues are as follows: (1) Use of computer: the proportion of employees who frequently use computers at work, the cost of purchasing computers and other information processing equipment; (2) Use of the internet: the percentage of sales revenue generated by the company through the Internet; (3) Use of ICT (including computers, internet, software): use of ICT in key business activities of the company, such as products or services, production and business activities, marketing and customer relations, whether the Internet is used to improve products or services when conducting business activities, ICT support for various innovation activities, etc. Based on the above-mentioned survey information, we obtain the interpreted and explanatory variables as shown in Table 1.

Other variables are as follows. Firm R&D decision variables: when the company has internal R&D activities or external R&D activities, the company is considered to have an R&D investment decision with a value of 1; otherwise, the value is 0.Enterprise R&D expenditures: The corresponding internal R&D activities and external R&D activities are added up when the enterprise R&D decision variable is 1.Enterprise ICT decision variables and enterprise ICT investment costs: OECD defines ICT investment as the purchase of equipment and computer software for more than one year of production and considers that ICT consists of three parts – information technology equipment (computers and related hardware), communication equipment, and software. Combined with information from the questionnaire,

Table 1. Variable description.

	Variable name	Variable description
Innovation input intensity	R&D intensity($\ln(RD/L)$)	Logarithm of per capita R&D expenditure (yuan/person)
	ICT intensity($\ln(CIT/L)$)	Logarithm of per capita ICT investment (yuan/person)
Innovation types	Product Innovation(PD)	When the company has product or service innovation, the value is 1; otherwise, it is 0.
	Process innovation(PCS)	When the company has process innovation behavior, the value is 1; otherwise, it is 0.
Innovation output	Product innovation output(PDI)	Sales from enterprise product or service innovation (yuan)
	Process innovation output($PCSI$)	Sales brought by enterprise process innovation (yuan)
Labor productivity	Per capita output($\ln(Y/L)$)	Logarithm of per capita output
Demand drivers	Export(EXP)	Dummy variable, whether the company has export behavior
Technology drivers	Foreign technology(FT)	Dummy variable, whether the company uses the technology license of a foreign company
	Standardization(STD)	Dummy variable, whether the company has internationally certified quality standards
	New equipment investment (NEI)	Dummy variable, whether the company invested in new equipment in the previous year
Company characteristics	Capital intensity(K))	Logarithm of capital to labor ratio (yuan/person)
	Company size($SIZE$)	Logarithm of the number of employees
	Company age(AGE)	The number of years the company has been in existence
	Labor quality(EDU)	Workers' years of education
	Type of company($TYPE$)	Dummy variable, classified as a private enterprise (1) or a state-owned enterprise (2)
Urban dummy Variables	City	Dummy variable for the city where the enterprise is located, assigned by the questionnaire city code
Industry dummy Variables	Industry	Dummy variable for the industry to which the company belongs, assigned by the industry code of the questionnaire

Data source: The World Bank innovation survey data of China.

this study takes the cost of computer and other information-processing equipment as the ICT investment cost. When the ICT investment cost is not zero, the company makes an ICT investment decision with a value of 1; otherwise, the value is 0.

Moreover, the enterprise questionnaire refers to the following innovation information: (1) Whether the company introduces new products or services; the proportion of sales brought by new products or services; (2) The proportion of production generated by the company's process innovation; (3) Specific innovation types of the company; and (4) The specific application of the company's product or service innovation and process innovation. Combining the questionnaires and data, we divide the company's innovation activities into product, process, and organizational innovation, which are defined as follows. Product innovation: This relates to the company introducing new or significantly improved products, while service innovation refers to new ideas and new technological means for new or improved service methods. This study regards new or significant improvements of a product or service as product innovation with a dummy variable equal to 1.

Product innovation output: The literature on CDM models generally uses patents or new product output values as innovation outputs, while this study takes the percentage of annual sales resulting from product innovation multiplied by annual sales

Table 2. Descriptive statistics: R&D and ICT innovation and productivity.

	Number of observations	Mean	Median	Std. Dev.
R&D	2,848	0.2683	0	0.4431
ICT	2,848	0.5713	1	0.4950
R&D investment intensity (yuan/person)	764	37,807.5	10,000	122,665.8
ICT investment intensity (yuan/person)	1,627	6,651.6	952.381	28,434.28
Labor productivity (per capita sales)	2,848	874,240.5	250,000	6,469,414
Product innovation	2,848	0.4751	0	0.4995
Product innovation output	2,848	37,700,000	1,335,000	471,000,000
Process innovation	2,848	0.4782	0	0.4996
Process innovation output	2,848	29,800,000	0	422,000,000

Source: Author's own calculation.

as the product innovation output. Process innovation: This refers to the use of new or significantly improved production methods, process equipment, or auxiliary activities, mainly reflected in technology, equipment, and processes, when the enterprise has process innovation, the virtual value is 1.Process innovation output: The calculation method is similar to that of the product innovation output. This study uses the percentage of annual sales resulting from technological innovation multiplied by annual sales as the process innovation output.

Other explanatory variables used in the CDM model include exports, technology drivers, and company characteristics. Export is a dummy variable whose value is 1 when a company conducts exports. Export can measure whether the enterprise could occupy the international market, and it also reflects the demand of the international market for the company's output. Companies with export behavior are expected to have greater competitive and learning effects, and to increase R&D and ICT investments. Combined with the enterprise questionnaire, this study selects foreign technology, standardization, and new equipment investment as the technology driving factors of. In the questionnaire, 'whether the company currently uses technology authorized by a foreign company', 'whether the company has internationally certified quality standards', and 'whether the company has introduced new equipment to improve its products or services' respectively indicate foreign technology Indicators, standardized indicators and new equipment investment indicators, when the company answers yes to these question, their value is 1, otherwise it is 0.

Heterogeneity exists among firms, and differences in capital intensity, size, and year of establishment can often result in differences in productivity. Thus, we include company characteristics such as capital intensity, size, company's age, and labor quality in the CDM model.

4.2. Descriptive analysis of Variables

The sample comprises 2,848 firms (of which 2,700 are private firms and 148 are state-owned firms), stratified by industry (20 industries according to the World Bank's enterprise survey data industry code) and geographical location (25 regions).

Descriptive statistics of the ICT and R&D investment-related and innovation variables are shown in Table 2. In the sample, 57.13% of companies invest in ICT, while a few companies (approximately 26.83%) invest in R&D. The proportion of ICT

Table 3. Results for R&D and ICT investment decisions.

	(I) R&D investment decision	(II) ICT investment decision
Capital intensity	0.1200***	0.0128
Size	0.1422***	0.0486
Export	0.4204***	0.2539*
Foreign technology	0.3912***	1.0062***
Standardization	0.2761***	0.3040**
New equipment investment	0.8063***	0.4380***
Company age	−0.0066*	−0.0045
Labor quality	0.0604***	0.0206
Constant term	−3.0702***	−1.8048*
City	YES	YES
Industry	YES	YES
Number of samples	2,848	2,848

Note: ***, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.
Source: Author's own calculation.

investment is higher than that of R&D investment for firms, which is consistent with the descriptive analysis results of Hall et al. (2013) and Alvarez et al. (2010). Contrary to the results concerning R&D and ICT investment decision-making behavior, the average R&D investment intensity is 37,807.5 yuan/person, which is much higher than the average ICT investment intensity of 6,651.6 yuan/person. Compared with making ICT investment decisions, companies are more cautious in making R&D investment decisions; however, results suggest that companies will invest more in R&D once R&D investments are made.

About 47.51% of companies introduced some type of product innovation, and 47.82% of companies introduced some type of process innovations. In general, the incidence of product innovation is approximately equal to the incidence of process innovation. Finally, the average labor productivity is 874,240.5 yuan/person. From Table 2, we can see that there is great heterogeneity in enterprise productivity, which is consistent with previous research (on an international basis). The average value of product innovation output is greater than that of the process innovation output, and at least half of the company's process innovation output is 0. The company's product innovation may bring more output than process innovation, and the two innovation outputs have obvious heterogeneity.

5. Empirical analysis

5.1. Innovation input equation of R&D and ICT

5.1.1 R&D and ICT investment decision analysis

The regression results of the R&D inputs' determinants can be obtained by using the probit model as shown in column (*I*) of Table 3. The results reveal that at a significant level of 1%, all explanatory variables, except for the company's age, have a significant positive impact on R&D investment decisions, with the technology-driven factors having the greatest impact. According to the research of relevant scholars, an enterprise's export behavior represents occupation of the international market; export can promote R&D and ICT investment by promoting competition and learning effects (Crespi & Zuniga, 2012). In this study, we also find that export has a positive

Table 4. Regression results for R&D and ICT investment intensity.

	(*I*) R&D investment intensity	(*II*) ICT input intensity
Size	−0.5148***	−0.4836***
Export	0.3489***	−0.1922**
Foreign technology	0.0831	0.3558***
Standardization	0.4283***	0.2655***
New equipment investment	0.4874***	0.1832*
Company age	0.0003	0.0004
Labor quality	0.0417	0.0211
Constant term	12.7720***	9.3830***
City	YES	YES
Industry	YES	YES
Number of samples	764	1,627

Source: Author's own calculation.

impact on R&D investment decisions with a coefficient of 0.4204, indicating that companies with export behavior are more willing to invest in R&D. In terms of company characteristics, the larger the company size, the younger the company and the higher the quality of the labor force, the more willing the company is to make R&D investments.

We also analyze the company's ICT investment behavior and find that the results, as shown in column (*II*) of Table 3, are similar to the R&D investment decision results. Technology drivers have the greatest impact on ICT investment, exports also have a significant impact on the ICT investments of firms at a significant level of 10%. On the contrary, company characteristics, such as company size, company age, and labor quality, have no obvious influence on ICT investment decision-making behavior.

Comparing the R&D and ICT investment decisions of firms, we find that technology drivers are very important for two innovation decision-making behaviors. Specifically, foreign technology and standardization have greater positive impact on ICT investment decisions, while the impact of new equipment investment on ICT investment decision is smaller than that on R&D. In summary, companies that are large and that have a high level of labor quality are more likely to invest in R&D than ICT. Technology can promote R&D and ICT investment, companies that use foreign technologies and have international certification quality standards pay more attention to R&D and ICT investments, especially the ICT investment; and new equipment investment is more conducive to firms' R&D activities, so it's beneficial to the R&D investment decision of firm.

5.1.2 R&D and ICT investment intensity analysis

This study uses the logarithm of per capita R&D and per capita ICT inputs as intensity indicators of R&D and ICT inputs, respectively. The regression results for R&D and ICT input intensity are shown in columns (*I*) and (*II*) of Table 4.

The regression results reveal that the larger the company, the lower the R&D and ICT investment intensity. Specifically, for every 10% increase in the company size, the R&D (ICT) investment intensity decreases by 5.848 (4.836) units. Relatively speaking, the company size has a greater negative impact on R&D investment. Exports are significantly correlated with R&D investment intensity, while its impact

Table 5. Regression results for innovation output.

	(*I*) Product innovation output	(*II*) Process innovation output
R&D input intensity	0.1507***	0.1645***
ICT input intensity	0.0875***	0.0730***
Size	0.0715*	0.1564***
Export	−0.0199	−0.0707
Foreign technology	0.2408*	0.3495**
Standardization	0.4012***	0.2742**
New equipment investment	1.1281***	1.2188***
Company age	0.1698**	0.1285
Labor quality	0.0313	−0.0431
Constant term	−4.0778***	−3.3041***
City	YES	YES
Industry	YES	YES
Number of samples	2,848	2,848

Source: Author's own calculation.

on ICT investment intensity is negative. Regarding technology-driven factors, the use of foreign technologies in companies has a significant positive impact on ICT investment intensity, but has no significant impact on R&D investment intensity; standardization and new equipment investment are positively correlated with ICT and R&D investment intensity, and the positive influence of the two factors on R&D investment is greater. Finally, No significant positive correlation was found between company age, labor quality and R&D and ICT investment intensity.

Technology-driven factors play an important role in both R&D and ICT investment intensity, and R&D investment intensity is more influenced by standardization and new equipment investment, while ICT investment intensity is more influenced by foreign technology. Having internationally certified quality standards and investing in new equipment are two characteristics of high-tech firms, and high-tech firms are more likely to carry out innovation activities. Therefore, the existence of these two technology-driven factors is likely to promote firms R&D investment. But ICT investments are more easily motivated by foreign technologies, probably because companies that use foreign technology are more dependent on ICT technology.

Comparing the probit model regression results of the two investment decisions in Table 3 with the linear regression results of the R&D and ICT investment intensity in Table 4, we find that the existence of demand factors (exports) and technology drivers not only help the company to implement decision-making behavior on innovation-related investments, but also basically promote the intensity of firms' R&D and ICT investment. This reflects the importance of demand and technology in R&D and ICT investment.

5.2. Innovation output equation

Based on the innovation output equations (6) and (7) of the CDM model, this study calculates the innovation output and analyze the results accordingly.

5.2.1. Product innovation output equation

Product innovation, as the driving force of enterprise development, has always been a focus of the enterprise innovation survey. Column (*I*) of Table 5 shows the regression results of the model for product innovation introduction, which is calculated according to equation (6). The results reveal that the effect of a company's size is similar to that of R&D intensity, that is, the innovation output increases as the enterprise size increases. Although exports play an important role in R&D and ICT investment decisions and investment intensity, there is no strong correlation between exports and product innovation output. In terms of other company characteristics, the company's age has a certain positive impact on product innovation output, with a coefficient of 0.1698, indicating that older companies are more inclined to engage in product innovation. Meanwhile labor quality does not show any impact on product innovation.

The three technology-driven factors all have positive effects on product innovation, among them, new equipment investment has the greatest impact. Investment is the main support for GDP growth, while new equipment investment is one of the main drivers of investment growth. Technology promotes innovation, as manifested by firms investing in new equipment, which in turn has positive impact on the output of product innovation. Firms that use foreign technology and have internationally certified quality standards have a strong tendency to innovate and are likely to engage in product innovation.

We mainly focus on the impact of R&D and ICT investment on innovation. The R&D and ICT investment intensity of firms have a significant positive impact on the product innovation output variable. Specifically, for every 10% increase in R&D (ICT) input intensity, the product innovation output increases by 1.507 (0.875) units. The positive impact of R&D investment on product innovation output is roughly twice as much as that of the ICT investment.

Previous studies by scholars on R&D investment have shown that companies can successfully achieve product innovation through R&D investment (Joseph et al., 1942; Segerstrom et al., 1990). Compared with R&D investment, ICT investment has a positive effect on the change of organizational approach and technological innovation model, but has a slightly weaker effect on the output of product innovation. These observations are consistent with our research results. In short, both R&D and ICT investments can promote product innovation, but R&D investment is more effective.

5.2.2. Process innovation output equation

Process innovation, embodied in technology, equipment, and processes, is an important way to improve the technical level and product-innovation ability of firms. It is also a necessary means to improve the competitiveness of firms. This section examines the impact of R&D investment intensity, ICT investment intensity, technological factors, exports, and company characteristics on process innovation output, focusing on the promotion of R&D and ICT investment intensity on process innovation.

The estimation results for the innovation output (equation (7)) are shown in column (*II*) of Table 5. Like the regression results for product innovation output, the three technical factors show positive impacts on process innovation output. New equipment investment has the largest impact on process innovation output, with a coefficient of 1.1281, which is consistent with the results for product innovation output. The coefficient of standardization is larger than that of foreign technology for product innovation output, while this coefficient relationship is just the opposite regarding technological innovation. Having internationally certified quality standards is very important for firms, especially for manufacturing firms, as it helps them manufacture high-standard and competitive products (which is closely related to product innovation); the use of foreign technology in equipment and processes improves process innovation. This difference is also reflected in the improvement of independent innovation ability of Chinese enterprises in terms of products. Compared with the direct introduction of foreign technology, the upgrading of the manufacturing quality of Chinese firms can better promote product innovation, while foreign technology better promotes process innovation.

The study of Hall et al. (2013) on the innovation and productivity of Italian manufacturing small and medium-sized enterprises (SMEs) showed that older companies are likely to engage in product innovation, but the company's age is not related to other types of innovation, which is consistent with the results of this study. Although older Chinese companies are more inclined to engage in product innovation, there is no strong correlation between the company's age and process innovation. Among the company's characteristics, the labor quality variables also have no significant impact on process innovation output. Moreover, we find that larger companies are more likely to implement process innovation, but exporters are less likely to introduce process innovation (the same results can be seen from Álvarez et al.'s research (2010) on the relationships among product innovation, process innovation, and productivity using data on Chilean manufacturing enterprises).

R&D investment intensity and ICT investment intensity of firms, which we are most concerned about, have obvious positive effects on the process innovation variables. Specifically, for every 10% increase in R&D (ICT) input intensity, the process innovation output increases by 1.645 (0.730) units. Clearly, R&D investment intensity has a greater impact on process innovation than ICT investment intensity.

In summary, both R&D and ICT investments have a positive and significant impact on product and process innovation outputs. Regarding product and process innovation, the company's R&D investment intensity is the most influential factor, and ICT investment intensity has a lower promotion effect than R&D investment intensity.

5.3. Labor productivity equation

Finally, we use equation (11) to examine the impact of innovation activities on productivity. Column (*I*) of Table 6 shows the results concerning the productivity function. To solve the endogenous problem, we use the forecast value of innovation output, which is estimated from the second stage of the CDM model. The results indicate that the impact of product innovation and process innovation on labor productivity is positive and significant at the 1% level. The coefficient of per capita capital to labor productivity is significantly positive, indicating that a deepening of capital can increase labor productivity. By contrast, larger companies have lower labor productivity. In column (*II*) of Table 6, the ICT investment forecast is introduced as an explanatory variable to test whether it directly affects productivity. The results show

Table 6. Regression results for labor productivity.

	(I) ln (y/l)	(II) ln (y/l)
Capital intensity	0.6077***	0.6071***
Size	−0.0374*	−0.0384*
Product innovation output	0.0166***	0.0164***
Process innovation output	0.0116***	0.0115***
	(2.62)	(2.58)
ICT investment		0.0026
Constant term	6.1756***	6.1807***
City	YES	YES
Industry	YES	YES
Number of samples	2,848	2,848

Source: Author's own calculation.

that both product innovation and process innovation are significant at the 1% level but the impact of ICT investment on productivity is not significant.

In summary, ICT and R&D investment have a significant impact on product innovation and process innovation, and product innovation and process innovation will directly affect enterprise productivity, but ICT investment has no significant impact on productivity, which contradicts practical experience. Therefore, this paper thinks that R&D and ICT investment may indirectly affect productivity through innovation and other activities. R&D and ICT investment can not only improve the efficiency of resource allocation, reduce the cost of tacit knowledge, but also can increase the possibility of product and process innovation, thus improving the productivity of enterprises.

6. Robustness test

To ensure the reliability of the research results, starting from the data, this section classifies the survey data according to the nature and size of the enterprise, and tests the robustness of the labor productivity equation.

6.1. Robustness test of different enterprise types

Based on the World Bank's enterprise questionnaire, the sample can be divided into private and state-owned firms. By applying the labor productivity equation above, this section examines the impact of capital intensity, firm size, product innovation output, and process innovation output on the labor productivity of different firms, with focus on product innovation and process innovation. The regression results are shown in Table 7.

The regression results reveal that the capital intensity of private and state-owned firms has a positive impact on labor productivity, and the influence of state-owned firms is slightly larger. Size of the two types of firms has no significant effect on productivity. The product and process innovation outputs of private firms have a positive and significant impact on productivity. However, there is no significant effect of the two innovation outputs on productivity in the regression results of state-owned firms.

Table 7. Regression results for labor productivity by enterprise type.

	(I) Private firms	(II) State-owned firms
Capital intensity	0.6003***	0.7822***
Size	−0.0281	−0.1294
Product innovation output	0.0165***	0.0284
Process innovation output	0.0142***	−0.0192
Constant term	5.8060***	4.7554**
City	YES	YES
Industry	YES	YES
Number of samples	2,700	148

Source: Author's own calculation.

Table 8. Regression results for enterprise labor productivity by size.

	(I) Small and medium firms	(II) Large firms
Capital intensity	0.6028***	0.6190***
Size	−0.0660***	−0.0176
Product innovation output	0.0126***	0.0278***
Process innovation output	0.0075	0.0175**
Constant term	6.3553***	6.0790***
City	YES	YES
Industry	YES	YES
Number of samples	2030	818

Source: Author's own calculation.

6.2. Robustness test of different enterprise sizes

The enterprise questionnaire divides the enterprises into three sizes according to the number of employees: small enterprises, with 5 to 19 employees; medium enterprises, with 20 to 99 employees; and large enterprises, with more than 99 employees. Correspondingly, this section divides the sample enterprises into small and medium enterprises (SME) and large enterprises with the boundary of 99.

The regression results are in Table 8, which shows that capital intensity has a positive impact on productivity for SME and large enterprises. For SME, the larger the enterprise, the lower the productivity, and there is an inverse "U" relationship between the enterprise size and productivity. This finding is consistent with those of various Chinese scholars (Sun & Wang, 2014; Gao et al., 2014), while this relationship is not found in large enterprises. For all enterprises, no matter the size, product innovation output shows a positive impact on labor productivity, but the impact of SME is lower than that of large enterprises. Moreover, the positive effect of process innovation output only appears on large firms. Product innovation generally relates to pure technological improvement, while process innovation reflects improvements in enterprise efficiency. Compared with small and medium firms, large firms often have bigger ability to integrate resources, and directly promote process innovation, which in turn has an impact on productivity.

Whether the sample is divided according to the nature or the size of the enterprises, the regression results show that the capital intensity index has a significant positive impact on labor productivity. Thus, product innovation output and process innovation output for both private and large-scale firms can enhance productivity.

7. Concluding remarks

By the world bank survey data on China, This study examines the effects of R&D and ICT on product innovation, process innovation, and on labor productivity based on an extended CDM model. The results reveal that both R&D and ICT investments can increase innovation output, and innovation output has a positive impact on productivity. Therefore, R&D and ICT investment can indirectly affect productivity.

Specifically, ICT investment decisions are mainly influenced by the technological driving factors (foreign technology, standardization, investment in new equipment), and R&D investment decisions are not only affected by technological driving factors, but also by capital intensity, enterprise size, exports, and labor quality. R&D and ICT investment intensity can promote product innovation and process innovation, for every 10% increase in R&D (ICT) input intensity, product innovation output increases by 1.507 (0.875) units, and process innovation output increases by 1.645 (0.730) units. Clearly, R&D input intensity has a greater impact on innovation output, and there is a positive correlation between innovation output and productivity according to the regression results of labor productivity, but this study does not find a direct impact of ICT on productivity. Instead, it finds that R&D and ICT investments indirectly impact productivity through innovation, because the increase in R&D and ICT investment can improve the efficiency of enterprise resource allocation, reduce costs, and increase innovation output, which are conducive to the improvement of productivity. In future research, different explanatory variables, such as the influence of different demand factors on the equation need to be considered more comprehensively to further improve the current equation.

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