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Empirical paper

Is innovation the key to solving the productivity paradox?

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ABSTRACT

The productivity paradox has sparked a great deal of research during the past three decades. Unfortunately, neither the results of empirical research nor the theoretical explanations for the paradox provide a convincing answer to whether investments in information and communication technology (ICT) affect the productivity of firms, sectors, and economies. This study aims to solve the productivity paradox by analysing the moderating effect of technological innovations on the link between ICT and productivity. The sample covers 2960 Polish innovative manufacturing firms. The research uses Generalized Structural Equation Model (GSEM). The findings clarify the productivity paradox and show that process innovations exert a moderating effect on the link between ICT and labour productivity in the sample firms.

Introduction

According to Porter and Millar (1985), investments in information and communication technology (ICT) are a source of competitive advantage. They argue that firms benefit from using ICT. On the one hand, ICT theoretically allows companies to perform activities in a faster, more accurate, and more flexible manner. On the other hand, ICT not only affects the way operational processes are performed, but also helps to improve the design of products to enhance their production. As such, many authors assume that ICT together with other investments including acquisition of machinery and training activities have a significant effect on a firm's productivity (Skorupinska & Torrent-Sellens, 2014).

In spite of the above-mentioned arguments, the positive link between ICT and productivity is not very clear. Solow (1987) refers to the lack of consensus among economists on the advantages of using ICT as the productivity paradox, which may occur at the micro level for different reasons. Firstly, firms may use ICT for purposes that do not target productivity growth directly. Secondly, some outlays on ICT are replacement investments that simply substitute an existing technology by a new up-to-date solution without fundamentally changing the nature of products and production processes. In the latter case, the key issue is to separate innovation-related ICT, which can affect productivity, from non-innovative ICT, which has no productivity effects. Although innovation seems to be the missing link between ICT and productivity, few empirical and theoretical studies focus on this issue (Hagén, Glantz, & Nilsson, 2008; Hall, Lotti, & Mairesse, 2013). In fact, most existing studies on the productivity paradox use a traditional approach, which treats ICT as one of many inputs in the production function. By doing so, they reduce the mechanism linking ICT with productivity to the causal chain that runs from the ICT use to productivity.

Going beyond the previous research in the field of productivity effects of ICT investments, this study applies a modified version of the well-known model of R&D, innovation, and productivity, called the CDM model (Crépon, Duguet, & Mairesse, 1998). These analyses offer an alternative solution to the productivity paradox by measuring the effect of ICT on productivity directly and indirectly. In the first case, ICTs in parallel with product and process innovations are inputs in a productivity equation. In the second case, ICT with other innovation-related investments enter into a new product and new process implementation equation as exogenous variables. This modification of the model's specification and structure leads to difficulties in estimation; therefore, the study uses a generalized structural equation model (GSEM) with a full-information maximum likelihood estimator. This technique enables the estimation of the entire model as one system, controlling for variables affecting productivity performance such

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Table 1
Results of some early and recent firm-level studies on ICT and productivity.

Study	Countries	Main findings
Yosri (1992)	United States	There is no significant correlation between IT investment, and productivity.
Weill (1992)	United States	Significant productivity can be attributed to transactional types of information technology, but there are no gains associated with strategic systems or informational investment.
Loveman (1994)	United States	The output elasticity of IT is negative.
Haltiwanger, Jarmin, and Schank (2003)	Germany, United States	The use of advanced technology such as information and communication technologies yields a greater increase in labour productivity in the U.S. than in Germany.
Maliranta and Rouvinen (2004)	Finland	The ICT-induced excess productivity seems to be higher in services than in manufacturing.
Stare et al. (2006)	Slovenia	There is a positive effect of ICT use on productivity.
Arvanitis and Loukis (2009)	Switzerland and Greece	There is positive effect of ICT on labour productivity.
Skorupinska and Torrent-Sellens (2014)	Bulgaria, Poland, Romania, Serbia, Ukraine	Models for country sub-samples show that country factors are significant in explaining labour productivity, mainly ICT infrastructure and management quality.

as firm size, technological opportunities, and export orientation (Bartelsman & Doms, 2000). The research employs a large sample of Polish manufacturing firms in the 2010–2012 period, extracted from the "Community Innovation Survey."

The next section provides the review of the literature on the productivity paradox and the use of ICT to introduce new products and processes, which may lead to higher productivity in firms. The following sections encompass a presentation of the model, data, and the results, followed by the conclusion and suggestions for further research.

Literature review and hypotheses

Productivity paradox: the macro and micro perspective

The Solow Paradox, concerning the limited evidence of ICT's positive effect on productivity, has been the subject of many studies. Solow's aphorism: "You can see the computer age everywhere but in the productivity statistics" (Solow, 1987) is still interesting, since it revolves around an unresolved economic question. The most comprehensive exploration of the productivity paradox at the macro level is the study by Oliner and Sichel (1994). They used the growth-accounting equation, which assumes that the rate of output growth equals the share-weighted growth in inputs plus the rate of growth of multifactor productivity. An estimation of the equation shows that even rapid rates of computing equipment/IT capital (i.e., information equipment and software) growth make relatively small contributions to growth when the share of this equipment is small. It is worth noting that the fall in IT capital prices should lead to a surge in investments in information technology and equipment. Jorgenson (2003) reports this situation and finds that the acceleration in the IT price decline in 1995 triggered a burst of IT investments and a rise in productivity growth in the IT-producing industries in all of the G7 countries. In line with these results, Dewan and Kraemer (2000) conclude that the productivity paradox is absent from developed countries but does exist in developing countries. The relatively small share of computers and information-processing technologies in Gross Domestic Product (GDP) is not the only possible explanation for the productivity paradox. Triplett (1999) presents an additional review of the conceptual issues in explaining the paradox. He stresses that measuring ICT and its effect on productivity correctly at the aggregate level is not a trivial task.

Taking into account the aforementioned issues in explaining the productivity paradox at macro level, firm-level analysis may allow overcoming some of these limitations. According to Pilat (2004), firm-level data can help to understand why outlays on ICT may not necessarily result in greater productivity, since it can point to factors/variables affecting the effects of ICT that cannot be directly measured at the aggregate level (e.g. innovation, firm size, the availability of skills, etc.). Furthermore, firm-level data gives the possibility of examining industry effects that may also affect ICT's influence. Ignoring the firm and industry-specific variables affecting productivity may bias the analysis and overestimate or underestimate the effect of ICT on productivity. Finally, firm-level data allows researchers to measure ICT with alternative proxies. Regarding empirical analyses, ICT expenditure is a desirable measure because it correlates with the ICT capital stock but is easier to use.

Table 1 presents the results of selected early and recent firm-level studies on ICT and productivity. Most of the early studies, which are comprehensively summarized by Brynjolfsson and Yang (1996), find either no effect or a negative effect of ICT on productivity. For example, a study by Yosri (1992), examining the relationship between ICT investments and revenue-contributing factors in 31 food firms in the period of 1987–1990, shows no significant correlation between IT expenditures and productivity. On the other hand, Loveman (1994), using a microeconomic production function to estimate the effect of IT on productivity, finds that the output elasticity of IT is negative. In turn, recent studies provide evidence that ICT can have a positive effect on a firm's productivity performance. As Stare, Jaklič, and Kotnik (2006), Arvanitis and Loukis (2009), and others show, ICT use has a positive effect on productivity. However, this effect may depend on a successive stage of ICT use sophistication (Miyazaki, Idota, & Miyoshi, 2012).

Comparing the results of early studies with the outcomes of recent works on ICT effects at firm level, the former usually draw on relatively small samples of firms, using non-official sources. This situation may result in non-representative samples and poor quality data. Moreover, early studies focus mainly on a direct relationship between ICT and productivity, neglecting an indirect ICT effect. Conversely, recent studies use large samples, which imply a greater quality and robustness of the data. Recent research has also advanced on the measurement of the indirect effect of ICT on productivity. Such progress owes to the availability of necessary data and the application of sophisticated econometric methods (e.g., structural equation modelling).

Innovation: the missing link between ICT and productivity

The application of ICT has a positive effect on a firm's productivity, which researchers have examined using a direct or indirect approach. The former is the traditional approach and is well grounded in the literature (Table 1). In turn, the latter allows decoupling ICT from productivity and is still the subject of intensive research. Despite the vast theoretical and empirical research focusing on the link between ICT and innovation and on the relationship between innovation and productivity, few studies treat ICT, inno-

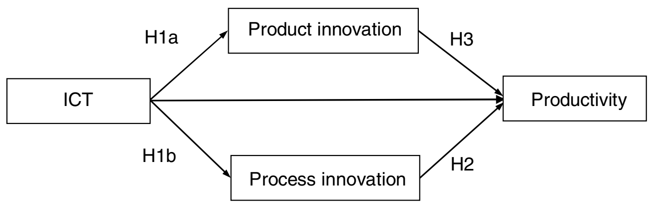

Fig. 1. Research model and hypotheses.

vation, and productivity as elements of the whole system and study them simultaneously.

The role of ICT in the innovation process and performance is twofold. First, a new ICT in a firm usually but not always involves innovation regarding the production process. According to the international method for collecting data on innovation activities, a process innovation is a new or significantly improved production or delivery method, including significant changes in techniques, equipment, and/or software (OECD, 2005). An example of ICT innovation is introducing electronic system linkages to streamline production and delivery processes. On the other hand, the introduction of new ICT can also be related to product innovation, which involves introducing a good or service that presents significant improvements regarding its characteristics or uses, technical specifications, components, materials, incorporated software, and user friendliness or other functional characteristics. It is important to note that with respect to services, it is difficult to distinguish process and product innovation related to ICT (OECD, 2005). In the case of goods, a new/innovative information technology may enhance product performance, as many products process information in their normal functioning (Porter & Millar, 1985). The empirical research conducted by Hempell (2002) suggests that the use of ICT is closely related to innovation in general and particularly to process innovation.

On the other hand, the use of ICT may positively affect the innovation process. For example, ICT, used as a "general purpose technology" (e.g., broadband internet), allows workers engaged in innovation to cooperate on the development of innovation with external agents such as suppliers, customers, competitors, academics, and international researchers. By exploiting network externalities, ICT makes it faster and more efficient for firms to respond to innovation opportunities. Furthermore, econometric analyses confirm that ICT plays an important role in developing innovations. Van Leeuwen and Farooqui (2008) show that the increase in a broadband penetration leads to the increase in innovative sales per employee. Hagén et al. (2008) report similar results.

Hypothesis 1. The propensity to ICT use positively affects innovation performance.

Hypothesis 1a. The propensity to ICT use positively affects the introduction of product innovation.

Hypothesis 1b. The propensity to ICT use positively affects the introduction of process innovation.

Identifying the link between ICT and innovation is the step that precedes the analysis of the relationship between innovation and productivity. The state of the art in theoretical and empirical research on a productivity effect of innovation reveals that its dependence on the innovation type (Hall et al., 2013). According to Lee and Kang (2007), process innovation may result in higher productivity performance than product innovation in the short run. They argue that process innovation is mainly aimed at changing the production process of the existing products to reduce costs, defects, wastes, and lead time, or improving production efficiency and eventually increasing sales. On the other hand, product innovation tends to face high defect rates and problems in the early stage of the product cycle that require adjustments. Because the adjustments need time, product innovation may possibly have a negative effect on productivity in the short term. Moreover, the market success of new products is not certain and a long time is required to ensure that new products are well known to the markets. Roper, Du, and Love (2008) also suggest that new products are likely to trigger the negative productivity effects of bespoke production (i.e., one-offs and small batches).

Hypothesis 2. Labour productivity increases with the propensity to introduce process innovation.

Table 2
Description of variables.

Variable	Description	Scale of measurement
PRODINN	Product innovation	Dummy variable: 1 if the firm developed or introduced new or improved products into the market during 2010–2012 period and 0 otherwise
PROCINN	Process innovation	Dummy variable: 1 if the firm developed or introduced new or improved process into the market during 2010–2012 period and 0 Otherwise
PRODUCTIV	Labour productivity	Logarithm of the firm's sale per employee in 2012
ICT	Purchase of ICT	Dummy variable: 1 if the firm was engaged in acquisition of ICT To develop and/or introduce new or significantly improved products and processes during 2010–2012 period and 0 otherwise
IRD	Internal R&D activities	Dummy variable: 1 if the firm was engaged in internal R&D during 2010–2012 period and 0 otherwise
AME	Acquisition of machinery and equipment	Dummy variable: 1 if the firm was engaged in acquisition of machinery and equipment to develop and/or introduce new or significantly improved products and processes during 2010–2012 period and 0 otherwise
TRAINING	Training activities	Internal or external training for the development and/or introduction of new or significantly improved products and processes during 2010–2012 period and 0 otherwise
HUMRES	Importance of lack of qualified personnel for innovation by the firm	Ordinal variable: from 1 (high importance) to 4 (no importance)
FINRES	Importance of lack of funds for innovation by the firm	Ordinal variable: from 1 (high importance) to 4 (no importance)
COMPET	Importance of competitors' innovation for innovation by the firm	Ordinal variable: from 1 (high importance) to 4 (no importance)

Hypothesis 3. Labour productivity decreases with the propensity to introduce product innovation.

Data and model

This study uses anonymized micro-data from the survey of innovation activities of Polish manufacturing enterprises in the years 2010–2012 provided by the Statistical Office in Szczecin. Enterprises hiring more than nine persons participated in the study. Sample selection draws on the Polish Classification of Activities, which is consistent with the statistical classification of economic activities in the European Community (NACE Rev. 2). The types of questions used in this survey are based on the Community Innovation Survey (CIS). Extensive piloting and pre-testing served to verify the interpretability and validity of the CIS questionnaire before implementing it within different European countries (Laursen & Salter, 2006). The sample of innovative firms used in this analysis comprises 2960 entities that developed and/or implemented product or process innovation in the years 2010–2012.

The chosen method to test the hypotheses was a structural model based on the CDM framework (Crépon et al., 1998). Crépon et al. (1998) offer a model of the link among innovation input, innovation output, and productivity. The CDM approach not only analyses the relationship between innovation input and innovation output, but also regards innovation output as a driver of productivity (growth). This study extends the CDM model by including the use of ICT as an enabler of product and process innovations and considers a direct causal relationship between the use of ICT and productivity (Fig. 1).

The model consists of three equations. There are two innovation output equations: one for process innovation and one for product innovation. Both equations include additional variables as possible determinants of innovation, which reflect a firm's engagement in different innovation activities (i.e., internal research and development activities, training for innovation, acquisition of machinery and equipment). In line with other studies in the CDM framework (Peters, 2008), the model controls for firm size, export orientation, and technological opportunities. The third equation is the productivity equation, which includes the innovation output measures for

Table 3
Estimates of GSEM parameters.

Equation/variables	Manufacturing enterprises			
	All ($n = 2960$)	Small ($n = 439$)	Medium ($n = 1709$)	Large ($n = 812$)
PRODUCTIV equation				
ICT	0.0745**	0.0408	−0.0131	0.0877
PROCINN	0.1474***	0.1412	0.0910**	0.1118
PRODINN	0.0452	−0.1159	0.0025	0.0613
COMPET	−0.1116***	−0.0818	−0.0923***	−0.1104***
HUMRES	0.0524***	0.0049	0.0473*	0.0885**
FINRES	0.2097***	0.1503***	0.1948***	0.1801***
CONST	5.1089***	5.2831***	5.1165***	5.3663***
PROCINN equation				
ICT	0.7356***	0.5165*	0.6784***	0.8950***
IRD	−0.4692***	−1.0390***	−0.4219***	−0.4431**
AME	0.8558***	1.2507***	0.7663***	0.7722***
TRAINING	0.6447***	0.8279***	0.5824***	0.5885***
CONST	−0.0227	−0.3269*	0.0106	0.2356
PRODINN equation				
ICT	−0.0903	−0.0239	−0.3006**	0.2253
IRD	0.8953***	0.9369***	0.6914***	1.2422***
AME	0.4977***	−0.0199	0.4929***	0.9458***
TRAINING	0.6028***	0.2648	0.7009***	0.5284***
CONST	−0.0432	0.2024	0.0163	−0.3774*
Equation/variables	Manufacturing enterprises			
	Export ($n = 2523$)	Non-export ($n = 437$)	Low tech ($n = 878$)	Med and high tech ($n = 2082$)
PRODUCTIV equation				
ICT	0.0615*	0.1394	0.0683	0.0708*
PROCINN	0.1543***	0.0339	0.2116***	0.1445***
PRODINN	0.0737**	−0.1771*	0.1341**	0.0031
COMPET	−0.0971***	−0.1651***	−0.1592***	−0.0900***
HUMRES	0.0527**	0.0322	0.0855**	0.0403*
FINRES	0.2174***	0.1491***	0.2283***	0.2007***
CONST	5.0567***	5.5025***	4.8855***	5.1854***
PROCINN equation				
ICT	0.6711***	1.1211***	0.9106***	0.6896***
IRD	−0.3698***	−1.1367***	−0.3045	−0.4310***
AME	0.9053***	0.5855**	1.3223***	0.6729***
TRAINING	0.6409***	0.6594***	0.2805	0.7753***
CONST	−0.0405	0.0781	−0.0234	−0.0570
PRODINN equation				
ICT	−0.0806	−0.1839	−0.1417	−0.0704
IRD	0.9051***	0.7807***	1.1189***	0.8395***
AME	0.5297***	0.3221	0.1928	0.6244***
TRAINING	0.5645***	0.7691***	0.5298***	0.6376***
CONST	−0.0133	−0.1553	0.2093	−0.1381

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Results of tests for the impact of ICT on productivity.

Test for impact of ICT on productivity	Manufacturing enterprises			
	All ($n = 2960$)	Small ($n = 439$)	Medium ($n = 1709$)	Large ($n = 812$)
	z statistic			
Direct	2.26**	0.40	-0.32	1.40
	Chi-square statistic			
Indirect through PROCINN	68.63***	5.49*	30.73***	21.84***
Indirect through PRODINN	2.56	1.37	5.80*	1.99
Total indirect	69.94***	7.91*	36.66***	23.78***
Total direct and indirect	82.20***	8.32	36.69***	27.69***

Test for impact of ICT on productivity	Manufacturing enterprises			
	Export ($n = 2523$)	Non-export ($n = 437$)	Low tech ($n = 878$)	Med and high tech ($n = 2082$)
	z statistic			
Direct	1.77*	1.44	1.10	1.83*
	Chi-square statistic			
Indirect through PROCINN	53.04***	16.55***	26.65***	46.59***
Indirect through PRODINN	4.48	4.00	4.94*	0.37
Total indirect	55.60***	21.12***	29.34***	47.09***
Total direct and indirect	64.58***	23.22***	33.36***	54.88***

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

both process and product innovation on the right-hand side. Firms' competitive pressure and the strength of their internal human and financial resources capture the ability to assimilate post-innovation productivity effects. Table 2 contains the description of the variables and the scales of measurement.

Formalizing the direct and indirect contributions of ICT use to productivity, we apply a structural-equations model (SEM). Structural equation modelling, a statistical method used in the behavioural sciences for the quantification and testing of substantive theories involves a combination of several traditional multivariate procedures such as factor analysis, regression analysis, discriminant analysis, or canonical correlation (Bagozzi & Yi, 2012). Most of response variables in the model are not continuous; therefore, the extension of the SEM model, Generalized SEM (GSEM), is applied (Rabe-Hesketh, Skrondal, & Pickles, 2004). In GSEM, response variables are not restricted to continuous variables, but they can be binary, ordinal, count, or multinomial. Three of the variables in the model are response variables: PRODUCTIV, PRODINN, and PROCINN. The PRODUCTIV variable is a continuous one and its equation is linear. In turn, the PRODINN and PROCINN variables are Bernoulli ones and their equations are probit regressions.

The study examines the effect of ICT on productivity using statistical tests. Testing the hypothesis about a parameter for an ICT variable in the productivity equation allows verifying the direct effect of ICT on productivity. The indirect effect through product innovation (or process innovation) is verified using the Wald test. The null hypothesis assumes that both the coefficient for the product innovation (or process innovation) variable in the productivity equation and the coefficient for the ICT variable in the product innovation (or process innovation) equation equal 0. The total indirect effect of ICT on productivity, through product innovation and process innovation, is verified using the Wald test for coefficients included in the product innovation and process innovation paths. Finally, the Wald test for all the indicated coefficients is applied to study the total (direct and indirect) effect of ICT on productivity.

Results and discussion

The first step consists in estimating the model parameters for all manufacturing enterprises. The analysis encompasses particular sub-samples of firms built according to size, export orientation, and sectoral classification. The results of the estimation of GSEM parameters for all enterprises, small, medium, and large firms, exporters and non-exporters, low technology, medium technology, and high technology firms appear in Table 3. Table 4 shows the results of the statistical tests for the verification of the direct and indirect effect of ICT on productivity.

The results of GSEM for all manufacturing enterprises indicate that the propensity to ICT investment has a twofold strong positive effect on productivity. First, the direct link between ICT and productivity is significant. Interestingly, the direct productivity effect of ICT investment varies depending on the firm's export orientation and a sectoral category. The effect of ICT on productivity is positive and significant within the groups of exporters and medium and high technology firms. Two important points emerge from these findings. On the one hand, the market pressure may induce a more productive ICT investment. On the other hand, the medium and high technology firms are probably more efficient in exploiting opportunities from ICT investment than low technology firms are.

Second, the indirect effect of ICT use on productivity is sensitive to the innovation type. In the case of process innovation, the use of ICT increases the firms' propensity to introduce a new process, which supports Hypothesis 1b. In turn, the results show that process innovation positively affects the sample firms' labour productivity (Hypothesis 2). Therefore, the indirect productivity effect of ICT through process innovation is clearly significant (Table 4). This outcome coincides partially with Hall et al. (2013), who find a positive effect of innovation on productivity. Contrary to expectations (Hypothesis 1a), in general, the use of ICT does not affect product innovation, which may be due to the fact that the sample firms probably make little use of ICT in a new product development process or introduce new products that do not deploy information technologies extensively. Moreover, the Polish manufacturing firms may not apply ICT to a new product development because of material (e.g., lack of financial resources) and non-material (e.g. lack of competencies) barriers. As regards the productivity effect of product innovation, a new product's effect on productivity is insignificant in the pooled sample. This result rejects Hypothesis 3. Another result shows that the positive effect of product innovation occurs for exporters and low technology firms. In the first case, one may assume that firms exposed to international competition are more efficient in innovation activity than non-exporters. In the second case, low technology firms usually introduce incremental innovations, which do not require production process adjustments.

Regarding other determinants of productivity, the results show that the strength of firms' resource base also proves important in determining performance. Of particular importance is the access to financial resources. One can well understand that the lack of financial constraints acts as a gateway for productivity-enhancing investments. Unsurprisingly too, firms that do not face human capital constraints also have higher productivity. In line with these results, the importance of workers' human capital in explaining productivity differences is also stressed by Syverson (2011) and other labour economists. Apart from internal factors, exposure to competition appears to affect firms' productivity, which means that firms increase their productivity when faced with competition. On this topic, Bartelsman and Doms (2000) review the role of competition in explaining productivity.

As regards the drivers of product and process innovations, the firms' engagement in internal R&D is significant for both process and product innovations. The model estimates (Table 2) show a positive effect of R&D investment on the probability of introducing product innovation, whereas the IRD coefficient is significantly negative with respect to process innovation. The negative effect of internal R&D on process innovation is also reported by Conte and Vivarelli (2005). The authors explain this fact by the existence of substitutability between innovation outputs. Our findings also confirm the results of recent microeconometric studies using data from the European Community Innovation Surveys, which show a close link between R&D expenditures and product innovation, and a strong relationship between innovative investment (especially devoted to new machinery/equipment and training) and process innovation (Conte & Vivarelli, 2013; Parisi, Schiantarelli, & Sembenelli, 2006).

Conclusions

This study examines firm-level relationships between ICT, product and process innovations, and productivity using data on Polish manufacturing firms. The main contribution is the consideration of the direct and indirect effects of ICT use on productivity. This approach acknowledges the existence of a moderating effect of technological innovation on the relationship between ICT and productivity. This approach also extends the CDM model to include the ICT investment as an enabler of product and process innovations and shows that ICT contributes directly to productivity. However, the indirect effect of ICT works mainly through process innovation. In this sense, the analysis suggests a dominant route by which ICT contributes to innovation and hence to productivity. In addition to highlighting the direct and indirect effect of ICT on productivity, this study emphasises the stimulating role of other factors in shaping firms' innovation performance and productivity. Interestingly, the quality of firms' human resources influences both innovation and productivity.

Beyond the presented results, this study paves the way for different avenues of research. For example, it might be interesting to apply various proxies for ICT capital using data explicitly designed to reflect the specific nature of different types of hardware and software packages. Our approach focuses on the link between ICT and productivity in one period, which remains a severe limitation. Therefore, future research should examine the productivity effect of ICT over time. Finally, it might be useful to explore the simultaneous relationship between ICT and productivity, since this study posits that the successful use of ICT leads to improved productivity, but improved productivity may lead to the successful use of ICT.

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