TFP, ICT and Absorptive Capacities: Micro-level evidence from Colombia

Juan Carlos Castillo[1] and Nicholas S. Vonortas[2,3]

[1] InSySPo Department of Science and Technology Policy, University of Campinas, Campinas-SP, Brazil
[2] Institute for International Science and Technology Policy & Department of Economics, The George Washington University, Washington-DC, USA
[3] São Paulo Excellence Chair, University of Campinas, Campinas-SP, Brazil

Abstract

This paper explores ICT investment and different types of absorptive capacity (realized and potential) as determinants of micro-level TFP in Colombia from 2008-2018. Our empirical output suggests that productivity is positively affected by ICT expenditures as well as by the presence of those IT-related potential absorptive capacities that strengthen knowledge acquisition and assimilation inside the plant: online transactions (e-commerce) and the use of network communication platforms(e-communication). Realized absorptive capacities such as R&D cooperation and marketing expenditures (signaling firms' ability to exploit and transform available information) are found to only induce TFP growth if combined with appropriate IT capabilities: R&D collaboration paired with e-communication and, marketing strategies connected with e-commerce. These results remain robust to various productivity indicators, issues of reverse causality (TFP-ICT link) and even to different IT-related proxies.

Keywords: Absorptive capacity; Firm-level; ICT; TFP; Colombia

JEL Classification: D24; O12; O30; O32; O33

1. Introduction

Over recent decades, the rise of the internet has drastically altered the operation of firms in aspects related to their organizational structures, transactional efficiency and even their production costs (Yu, 2022). These factors, coupled with an increasing pressure to achieve greater competitiveness based on knowledge innovation, are progressively pushing more firms to invest on information and communication technologies (ICT). Acknowledging such scenario, this research aims to evaluate the extent by which firms' productivity is affected by the adoption of ICT as well as by the nurturing of different absorptive capacities inside the organization.

To meet this objective, Colombia will be referred as a case study. This country has lately implemented numerous policies for the digital transformation of its economy which seek to foster foreign investment at the ICT sector, promote the emergence of technology-based start-ups, nurture the advancement of creative industries as well as the breeding of skills for Industry 4.0. Furthermore, according to the OECD (2019), Colombian firms employing more than 10 workers scored by 2015 a higher-than-the-world average internet connection level which was, nonetheless, heavily conditioned by limited broadband penetration. In our view, such factors shaping the Colombian case serve as highly appropriate for the assessment of ICT and related capabilities as they accentuate the challenges that are yet to be solved by developing countries on their attempt to digitalize its manufacturing base.

A unique dataset is herein prepared to adequately address such technological trends across Colombian firms. By relying on various sources of official information, our research generates a single dataset that jointly reports industrial and innovation statistics together with data on ICT-related variables at the establishment level over a ten-year span (2008-2018).

This research deviates from previous studies in that we highlight (and test) the effect of three types of absorptive capacity on TFP: the one emerging from a knowledge assimilation and acquisition competence (known as potential absorptive capacity); the one stemming from a knowledge transformation and exploitation ability (known as realized absorptive capacity); and the one that originates from the interaction between these two.

To account for its corresponding influence on plants' productivity, the absorptive capacity concept has been exclusively operationalized as a single indicator in relation to variables pertaining to R&D expenditures, human capital investment, organizational structure and so forth (Augier et al., 2013; Foster-McGregor et al., 2016; Howell, 2020). Notwithstanding the fact that the empirical measure of such latter signifies a challenging task (Rothwell and Dodgson, 1991), in our view, the use of a single absorptive capacity proxy leads to a meager understanding on the specific reasons why some plants are able to extensively benefit from the nurturing of such competences while others fail to do it so (especially, when less developed economies are taken into account). In consequence, by addressing the TFP impact that originates from potential and realized absorptive capacities (as well as the one stemming from their interaction), our research aims to fill an important empirical gap on the process whereby firms build and endure their competitive edge.

Our econometric evidence suggests that TFP is positively configured both by ICT investment as well as by the deployment of IT-enabled potential absorptive capacities such as online transactions (e-commerce) and the use of network communication platforms (e-communication). On the other hand, TFP does not seem to be affected by other pivotal non-IT related capabilities (like marketing expenditures and collaborative R&D projects) despite their critical role in allowing firms process and exploit available knowledge. These two latter realized capacities are found to only matter for productivity growth if combined with a given IT competence: e-communication paired with R&D collaboration and, e-commerce combined with marketing expenditures.

Strong policy implications for emerging economies can be derived from this quantitative research. The outcomes here presented seem to not only emphasize the specific type of investment to be performed, but also the various technological instruments, networks and skills to be acquired and nurtured at the firm-level in order for these countries to progressively induce a profound digital transformation across manufacturing enterprises, increase their productivity performance and solidify a competitive edge.

This research is structured as follows. Section 2 shows our theoretical framework on the ICT and absorptive capacity elements that shape TFP at the company-level. From this theoretical discussion, we derived our general hypotheses. Section 3 introduces our main sources of micro-level information and discusses our econometric strategy to account for potential endogeneity concerns on the link between TFP and ICT investment. Section 4 presents our main results. This latter section also highlights the robustness of our econometric output by accounting for various productivity indicators and different IT proxies. Section 5 concludes this research.

2. Theoretical framework

Given the large-scale availability of longitudinal manufacturing datasets, total factor productivity (TFP) has become a quintessential indicator to describe firms' technical efficiency. Following the seminal contribution by Solow (1957), TFP is generally computed as a residual from a given production function once output and input growth have been accounted for. Some of the key methods to estimate TFP at the plant level include non-parametric estimations such as index number (Caves et al., 1982), parametric techniques like system GMM (Blundell and Bond, 2000), as well as various semi-parametric analysis which aim to tackle issues of selection bias and endogeneity concerns due to potential links between unobserved productivity shocks and inputs comprising the production function (Olley and Pakes, 1996; Levison and Petrin, 2003; Ackerberg et al., 2005)

The role played by ICT investment in configuring firms' productivity has received widespread attention given the ongoing fourth industrial revolution. ICT can be defined as those electronic means available to the firms which enable and facilitate an ample range of activities that relate to the storage, processing, distribution, transmission, and reproduction of information thus enabling a process of learning from others both inside and outside firms' boundaries (Aghion, 2002).

Firms investing on inter-organizational information systems, internet-based procurement schemes and infrastructure for electronic data exchange have faced significant drops on administrative and search costs (Marsh et al., 2017). Faster and improved communication with customers and suppliers, access to new business opportunities, higher internal efficiency and, in general, the reduction of any market failures that are associated with information asymmetries, represent some additional benefits being triggered by the use of ICT (Fulantelli and Allegra, 2003; Giotopoulos et al., 2017)

Nonetheless, the adoption of those technologies is not exempted from obstacles. Firms adopting ICT need to cope with a number of expenditures that are not solely linked to the upgrading of the existing communications facilities, but that also entail supplementary investments on software and hardware licensing, the training of employees for the acquisition of digital skills, processes of organizational restructuring and so forth (Tan et al., 2010; Ghobakhloo et al., 2011).

By relying on different ICT proxies, various empirical studies have corroborated the positive impact that this type of investment exerts on firms' productivity (Cardona et al., 2013). These proxies encompass total computers' spending (Brynjolfsson and Hitt, 2003), measures for firms' IT capital stock (Brynjolfsson et al., 2002; Bloom et al., 2012), indicators for ICT intensity (Autor et al., 1998; Acemoglu et al., 2012, Hall et al., 2013), as well as variables pertaining to the adoption of IT equipment like the installation and use of 3D CAD software, automatic inspection sensors (Bartel et al., 2007) or even the number of workers utilizing ICT inside the plant (Greenan and Mairesse, 2000) to name a few.

Based on these arguments, we then expect ICT investment to positively shape TFP. Nonetheless, in empirical testing this hypothesis, reverse causality concerns are to be acknowledged (Papaioannou and Dimelis, 2007; Minetaki and Omori, 2010; Mitra et al., 2016). In consequence, an instrumental variable appraisal explicitly dealing with the potential endogeneity of ICT needs to be accounted for.

H1: ICT positively impact TFP.

The impact of ICT on productivity can also be mediated by firms' absorptive capacity (Marsh et al., 2017). According to Cohen and Levinthal (1990), absorptive capacity can be defined as the ability possessed by a given firm to identify, integrate, process and exploit external knowledge in order to rapidly adapt to changes in the environment and strengthen the company's competitive position. Absorptive capacity can be regarded as one of the firms' dynamic capabilities (Teece et al., 1997) and play a critical position in configuring long-term competitive performance (Wang and Ahmed, 2007).

Empirically quantifying the prevalence of absorptive capacity within the organization signifies a challenging task given the multi-dimensional and intangible essence of this concept (Rothwell and Dodgson, 1991; Matusik and Heeley, 2005; Schmidt, 2010). Indicators signaling firms' relative distance to the industry-level technological frontier (Girma, 2005; Kim 2015), R&D expenditures (Lokshin, et al., 2008; Howell, 2020), human capital investment (Augier et al., 2013; Yasar, 2013), organizational structure and management practices (Lane et al., 2006, Schmidt, 2010) amount to some of most the commonly used proxies for absorptive capacity.

Absorptive capacity can act as a point of reference to moderate productivity improvements as well as an element to solidify the efficiency benefits that are obtained from the use of other company-specific features. For instance, firm-level productivity gains (derived from factors such as FDI or ICT adoption) have been described to vary depending upon a certain absorptive capacity threshold (Girma, 2005; Marsh et al., 2017; Howell, 2020; Moralles and Moreno, 2020). Raising the TFP effect from FDI (Wang, 2010), strengthening the link between higher productivity and higher imported intermediate consumption (Augier et al., 2013; Yasar, 2013; Foster Mc-Gregor et al., 2016; Okafor et al., 2017), along with its role in configuring intra and inter-industry productivity differentials (Liao et al., 2012) embody a few additional effects that originate from the presence of absorptive capacity.

Potential and realized capacities are regarded as the two key subcomponents that configure the idea of absorptive capacity (Zahra and George, 2002). Potential absorptive capacity (PACAP) refers to the process whereby firms acquire and assimilate knowledge through increasing communication and collaboration with external partners. Realized absorptive capacity (RACAP), on the other hand, deals with the ability inside the organization to effectively transform and exploit the previously gained external knowledge through the deployment of special skills such as the use of advanced manufacturing technologies, marketing strategies and the like (Raymond et al., 2015; Min et al., 2019).

Factors pertaining with external information acquisition and intra-firm knowledge dissemination typically encompass some of the most utilized proxies for PACAP (Liao et al, 2003; Cepeda et al., 2012). These include variables underscoring firms' interactions with headquarters (in order to acquire new knowledge), the collection of industry-level information through formal and informal meetings, the ability to quickly identify new opportunities to serve clients, and so forth (Jansen et al., 2005).

On the other hand, networking and marketing capabilities constitute two relevant firm-level features to account for the presence of RACAP inside the organization (Raymond et al., 2015). Networking reflects firms' adeptness to fruitfully exploit relationships with business partners as a means to gain and sustain competitive edge (Powell et al., 1996; Greenly et al., 2005). Sharing technical risk, generating technological conventions, reaching new consumers and the like stand as key factors encouraging networking across firms (Dodgson, 1993; Vonortas, 2012).

Marketing capabilities comprehend those strategies aiming to meet consumers' demands (Weerawardena, 2003). Organizations investing monetary resources on the setting up of pricing tactics, alternatives for product development, and marketing communication schemes generally improve their competitive performance and even manage to reduce their lag with respect to industry leaders (Kaplan and Norton, 2008; Nedelko and Potočan, 2016)

Each of these two subcomponents of absorptive capacity can be individually affected by the presence of different organizational mechanisms. For instance, in line with Jansen et al.

(2005), coordination capabilities (comprising job rotation, cross functional interfaces and participation in decision making) positively configure PACAP, while RACAP seems to be strengthen by socialization capabilities such as connectedness and/or socialization tactics.

Even more so, given their complementarity nature, various empirical studies have determined that PACAP can exert a positive effect over RACAP (Limaj and Bernroider, 2019; Algarni et al., 2023) and, that interaction of these two can also generate a joint impact over innovation performance (Saraf et al., 2013; Crescenzi and Gagliardi, 2018). Nevertheless, the extent through which such PACAP-RACAP link takes places inside the organization has also been argued to vary depending upon supplementary features such as cultural barriers (Leal-Rodriguez et al., 2014), structural ambidexterity (Elidjen et al., 2022), organizational climate for innovation (Contreras et al., 2021), and information systems (Cepeda et al., 2012) to name a few.

Given current technological trends, IT-enabled potential and realized absorptive capacities can also emerge within the organization (Joshi et al., 2010). For the case of PACAP, information technologies can assist on the efforts to nurture acquisition capabilities through the use of internet platforms such as e-commerce (Raymond et al., 2015). Internet sales and procurement enhance the intensity, speed, directionality and selection of strategic knowledge inside the firm as they allow for a tighter and real-time interaction with consumers and suppliers. Along the same lines, IT can also foster assimilation capabilities by creating electronic repositories (in the form of intranet and extranet infrastructure) which then constitute an integral part of the firms' organizational memory (Alavi and Leidner, 2001).

With regard to RACAP, and following the ideas posed by Joshi and colleagues, we observe that IT positively influences knowledge transformation and exploitation capabilities by providing tools which permit the categorizing, reclassifying and synthesizing of new acquired information. Tools like cloud computing, data mining, specialized analytical software and so forth account for the factors that support the process of knowledge transformation. On the other hand, elements such as expert-systems and case-based reasoning (which configure artificial intelligence technologies) comprise some of the IT features that enhance knowledge exploitation capabilities (Joshi et al., 2010).

Some of the recently advanced PACAP and RACAP related variables have been found to positively shape firms' total factor productivity. This is the particular case of marketing expenditures (Roth et al., 2023), R&D networking (Dai et al, 2022), use of intranet and extranet infrastructure (Shin, 2000) and e-commerce (Rincon et al., 2005; Bassetti et al., 2020; Rizov et al., 2022).

Nevertheless, to the best of our knowledge, the influence that those factors exert over TFP has not yet been explicitly addressed through the lenses of an absorptive capacity's framework. Even more so, aside from highlighting a positive TFP impact emanating from those latter PACAP and RACAP proxies, such later theoretical framework would also suggest the prevalence of a complementarity effect: an additional TFP effect derived from the interaction between PACAP and RACAP inside the organization. In this background context, we raise the following expectations.

H2 PACAP positively impact TFP.

H3: RACAP positively impact TFP.

H4: PACAP and RACAP interact and complement one and other and thus, they jointly positively impact TFP.

3. Methodology and sources of information

This section summarizes our empirical strategy to econometrically evaluate the impact of ICT investment and absorptive capacities over firms' productivity. To execute this analysis, we will utilize three sources of micro information on Colombian manufacturing that separately address industry related variables, trends on communication technologies (the EAM and EAM-TIC dataset, respectively), and statistics pertaining to innovation performance (the EDIT dataset).

Firm-level information for Colombian manufacturing is reported in the context of the annual industrial survey known as EAM (*Encuesta Annual Manufacturera*). Colombia's Statistical Office (DANE) compiles and produces this official dataset which discloses microeconomic statistics at the three digit-level (ISIC, rev. 4), for key industrial variables (in line with the country's national accounting system) considering those manufacturing establishments employing more 10 workers. From 2008 to 2018, DANE decided to expand the scope of EAM by collecting additional data that relate ICT adoption (EAM-TIC dataset). Expenditures on ICT infrastructure, total number of available computers, laptops and tablets, type of broadband service being utilized and even the implementation of internet-based work strategies (such as home-office) constitute the most relevant variables included on this special module of the EAM survey (DANE, 2020).

On the other hand, information referring to the innovation activities taking place inside Colombian plants are divulged by DANE through a biannual study named EDIT (*Encuesta de Desarrollo y Divulgación Tecnológica*). Our research decided to rely on the 4th to 9th consecutive waves of these innovation surveys (that comprehend the years between 2007 to 2018) in order to closely match this period of analysis with the one outlined by the industrial surveys. Moreover, given the availability of a standardized plant-id, we managed to link these three datasets (EAM, EAM-TIC and EDIT) thereby generating a single dataset that together explains manufacturing, ICT and innovation trends for a large number of establishments (10,920 firms) over a ten-year span.

We now proceed to delineate our baseline econometric specifications, the set of dependent and independent variables to be utilized, as well as their operationalization. Appendix (A.1) and (A.2) provide further details on the specific proxies herein employed and their corresponding descriptive statistics, respectively.

Equation (1) depicts our econometric strategy. The impact of ICT and absorptive capacities on firms' productivity will be assessed by relying on three separate dependent variables that relate to different methodologies to compute plant productivity; TFP-OP (Olley and Pakes, 1996), TFP-LP (Levinsohn and Petrin, 2003) and LPROD (a gross value added to labor ratio, signaling the standard method to compute labor productivity). Following established procedures, unobserved productivity shocks will be addressed by utilizing proxies for capital investment (TFP-OP) and intermediate inputs (TFP-LP), respectively.

$$Productivity_i = \beta_1 size + \beta_2 age + \beta_3 ICT_{inv} + \beta_4 IT_{PACAP} + \beta_5 R\&D_{coop} + \beta_6 MKT + \beta_7 \left(IT_{PACAP} * R\&D_{coop}\right) + \beta_8 (IT_{PACAP} * MKT) + \omega_0 \quad (1)$$

Yearly expenditures on informatics and office equipment comprise our variable for ICT investment (ICT_{inv}). Acknowledging reverse causality concerns between productivity and ICT investment, our research pursued an IV-regression approach (Papaioannou and Dimelis, 2007; Minetaki and Omori, 2010; Mitra et al., 2016). As an appropriate instrument, we employed the percentage share of workers that utilize the internet inside the organization (Greenan and Mairesse, 2000). In our view, this latter instrument effectively captures the effect of ICT investment on TFP since it reflects the extent through a given company depends upon web-based tools to perform job-related duties.

E-commerce and e-communication will be separately included in equation (1) as IT-enabled PACAP (IT_{PACAP}) and portrayed in the form of binary observations. $E\_commerce$ deals with the presence (or lack thereof) of online transactions (both sales and procurement), while $E\_communication$ addresses the absence (or prevalence) of intranet and extranet digital platforms to ease relations across firms' partners.

Our research was unable to include at equation (1) IT-enabled RACAP proxies (specialized software, cloud computing, artificial intelligence, internet of things and so forth). Instead, we added other critically relevant non-IT-related RACAP such as R&D collaboration and marketing activities. These are too include as dummy variables and signify the allocation of monetary resources on advertisement and representation costs (MKT), as well as the prevalence of third-party funding to cooperation on inventive projects ($R\&D_{coop}$).

In line with the ideas outlined during our theoretical framework, equation (1) introduces an interaction effect pairing IT-PACAP proxies with non-IT RACAP indicators: ($IT_{PACAP} * R\&D_{coop}$) and ($IT_{PACAP} * MKT$). This approach then entails running several regressions whereby the e-commerce and e-communication variables are separately interacted with marketing and R&D collaboration proxies. Size (total labor), age (number of years operating in the market) along with regional, sectoral and yearly dummies are too incorporated as supplementary control variables.

4. Results

Econometric results are presented in tables (1) and (2). Following equation (1), each of these tables separately deals with e-commerce and e-communication, respectively. IV regression output is therein reported considering three dependent variables: TFP-OP, TFP-LP and LPROD. For every estimation being shown, ICT_{inv} was found as being endogenous at about the 1% level (Hausman test). F-statistics (not here reported) rejected the null of a weak instrument thereby validating our IV coefficients as unbiased and not suffering from large standard errors.

Table (1). IV regression on productivity determinants: e-communication

	TFP-OP	TFP-LP	LPROD
ICT_inv	0.415^{***}	0.371^{***}	0.399^{***}
	(0.03)	(0.03)	(0.03)
Size	0.003	-0.143^{***}	-0.500^{***}
	(0.02)	(0.02)	(0.02)
Age	0.126^{***}	0.066^{***}	0.146^{***}
	(0.02)	(0.02)	(0.02)
E_communication	0.212^{***}	0.122^{***}	0.238^{***}
	(0.03)	(0.02)	(0.02)
R&D_coop	0.098	-0.049	0.111
	(0.16)	(0.15)	(0.14)
*R&D_coop*E_commun.*	0.567^{**}	0.658^{***}	0.558^{***}
	(0.17)	(0.16)	(0.14)
MKT	0.067	0.082	0.003
	(0.04)	(0.08)	(0.08)
*MKT*E_commun.*	0.052	-0.024	0.130
	(0.05)	(0.08)	(0.08)
constant	-1.653^{***}	-5.982^{***}	4.925^{***}
	(0.06)	(0.05)	(0.05)
R^2	0.328	0.189	0.275
Observations	25,643	25,643	32,458

Note: Robust standard errors in parentheses. For every specification, regional, yearly and sectoral dummies are herein included. *Job_internet* (percentage share of workers using internet inside the plant) is employed as an instrument for each IV regression. Hausman tests confirmed the endogeneity of ICT_inv at about 1%. F-statistics reject the null of a weak instrument (coefficients are unbiased and do not suffer from large standard errors). TFP-OP (Olley and Pakes, 1995), TFP-LP (Levinsohn and Petrin, 2003), LPROD (gross value added to labor ratio).
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table (2). IV regression on productivity determinants: e-commerce

	TFP-OP	TFP-LP	LPROD
ICT_inv	0.354^{***}	0.329^{***}	0.332^{***}
	(0.03)	(0.03)	(0.03)
Size	0.036	-0.121^{***}	-0.466^{***}
	(0.02)	(0.02)	(0.02)
Age	0.115^{***}	0.059^{**}	0.134^{***}
	(0.02)	(0.02)	(0.02)
E_commerce	0.303^{***}	0.194^{***}	0.332^{***}
	(0.03)	(0.03)	(0.02)
R&D_coop	0.138	-0.024	0.137
	(0.16)	(0.15)	(0.14)
*R&D_coop*E_commerce*	0.737^{***}	0.740^{***}	0.649^{***}
	(0.17)	(0.16)	(0.16)
MKT	-0.076	-0.101	-0.025
	(0.07)	(0.07)	(0.06)
*MKT*E_commerce*	0.198^{**}	0.182^{**}	0.175^{**}
	(0.07)	(0.07)	(0.07)
constant	-1.778^{***}	-6.063^{***}	4.795^{***}
	(0.06)	(0.05)	(0.05)
R^2	0.340	0.206	0.285
Observations	25,643	25,643	32,458

Note: As described in table (1). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

From either table, we confirm our expectations on H1 since ICT investment shows a positive and statistically significant impact on productivity regardless of the dependent variable being assessed. We also corroborate H2 since both proxies for IT-enabled PACAP (e-commerce and e-communication) report a positive impact on productivity. Unlike our expectations, we reject H3 since R&D collaboration and marketing (RACAP proxies) are found as being irrelevant for productivity improvements. This underscores the idea that firms operating in less developed economies might actually face important difficulties to successfully benefit from their RACAP in spite of explicitly allocating monetary resources for their nurturing.

Nevertheless, interesting results arise once we analyze the interaction effect between PACAP and RACAP. On the one hand, e-commerce and e-communication positively strengthen the effect of marketing on TFP (and on labor productivity) since the combination of either IT-PACAP with marketing expenditures is found to induce productivity gains. On the other hand, given their specific nature, R&D collaboration seems to only yield a positive and significant effect on productivity if combined with e-communication. E-commerce does not seem to play a role in strengthening the TFP effect originating from scientific cooperation. Our expectations on H4 are thus confirmed.

We also utilized different IT-PACAP proxies to further test the robustness of our econometric output. Following previous empirical studies, the use of local area networks (LAN) comprised a second proxy for e-communication (Shin, 2000; Minetaki and Omori, 2010), while e-commerce was then portrayed as a binary indicator for website adoption (Rizov et al., 2022). These econometric results are presented at tables (A.3) and (A.4), respectively.

As can be observed, employing these new IT-proxies does not drastically alter our IV results. IT-PACAP variables have a positive impact on either measure of technical efficiency and generate additional productivity improvements if connected with appropriate RACAP indicators. R&D collaboration also appears to only produce productivity gains when paired with the use of LAN network, whereas marketing strategies appear to largely benefit both from the use of those same communication platforms as well as from the online presence of the firm.

5. Conclusions

This paper analyzed ICT investment and absorptive capacities as determinants of plants' productivity at a major emerging economy. To this end, we utilized a novel micro dataset on Colombian manufacturers that conveniently reports information on innovation and ICT-related expenditures from 2008-2018. Unlike existing research, our work analyzed the TFP impact induced by potential and realized absorptive capacities as well as the one emerging from the interaction of these two. Reverse causality concerns derived from the TFP-ICT link were also here accounted for. Our general research can be then summarized as follows.

When assessed in isolation, PACAP and RACAP matter differently for firms' TFP. IT-enabled PACAP (such as e-commerce and e-communication) positively configure productivity growth, while other non-IT RACAP (like marketing strategies and R&D collaboration) do not seem to report a statistically significant effect on this. RACAP are only found to have a positive impact on TFP if paired with an appropriate IT-enabled PACAP.

Such empirical finding heavily supports one of the key arguments discussed during our theoretical framework on the fact that PACAP and RACAP interact and complement one and other during the process of building companies' competitive edge. In line with prevailing quantitative studies, we also corroborated the positive role played by ICT expenditures in shaping TFP growth. These latter set of results remained robust to various productivity indicators and different PACAP proxies.

Inducing a growing number of firms to invest on and adopt ICT technologies coupled with strategies for a steady nurturing of IT-related capabilities comprise the main policy recommendations from this work. Our results underscore the fact that ICT (and their linked competences) are critical elements to increase technical efficiency and to fully exploit those additional productivity gains stemming from other non-capital investment inside the organization (marketing and R&D collaboration).

Emerging economies, like Colombia, might lack the adequate skills to successfully capitalize on the productivity gains that are associated to their RACAP investment. IT-enabled capabilities then can be erected as feasible alternatives to strengthen the efficiency gains of marketing and R&D collaboration thus further solidifying the building of a competitive advantage over time.

Future research should aim to not only test the TFP effect from IT-PACAP but also that of IT-RACAP, which is embodied on the presence of specialized software, cloud computing, artificial intelligence and, so forth. Our research has provided the building blocks to further analyze these trends by pointing out the relevance of IT-enabled PACAP and their pivotal role on reinforcing RACAP as an option for higher productivity gains.

References

Acemoglu D., Dorn, D., Hanson G. H., and B. Price (2014), "Return of the Solow paradox? IT, productivity, and employment in US manufacturing", *American Economic Review*, 104(5), 394–399.

Ackerberg, D. A.; Caves, K. and G. Frazer (2005), Structural Identification of Production Functions (mimeo: University of California at Los Angeles).

Aghion P. (2002), "Schumpeterian Growth Theory and The Dynamics of Income inequality", *Econometrica*, 70, 855–882.

Alavi, M., and D.E. Leidner (2001), "Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues", *MIS Quarterly*, 25(1), pp. 107–136. https://doi.org/10.2307/3250961

Algarni, M.A., Ali, M., Leal-Rodríguez, A.L. and G. Albort-Morant (2023), "The Differential Effects of Potential and Realized Absorptive Capacity on Imitation and Innovation Strategies, and its Impact on Sustained Competitive Advantage", *Journal* *of Business Research*, Vol. 158, 113674, https://doi.org/10.1016/j.jbusres.2023.113674.

Augier, P., Cadot P., and M. Dovis (2013), "Imports and TFP at the Firm Level: The Role of Absorptive Capacity", *Canadian Journal of Economics*, 46, 3, pp. 956–81.

Autor, D. H., Katz L.F., and A. B. Krueger (1998), "Computing Inequality: Have Computers Changed the Labor Market?", *Quarterly Journal of Economics*, 113(4): 1169–1213.

Bartel A., Ichniowski C. and K. Shaw (2007), "How does information technology affect productivity? Plant-level comparisons of product innovation, process improvement, and worker skills", *The Quarterly Journal of Economics*, 122(4), 1721–1758.

Bassetti, T., Borbon Galvez, Y., Del Sorbo, M., and F. Pavesi (2020), "Artificial Intelligence – Impact on Total Factor Productivity, Ecommerce & Fintech", EUR 30428 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-24693-0, doi:10.2760/333292 , JRC122268

Bloom N., Sadun R. and J. Van Reenen (2012), "Americans do IT better: US multinationals and the productivity miracle", *American Economic Review*, 102(1), 167–201.

Blundell, R. W. and S. R. Bond (2000), "GMM Estimation with Persistent Panel Data: Application to Production Functions", *Econometric Reviews*, 19 (3), pp. 321-340.

Brynjolfsson E. and L. M. Hitt (2003), "Computing productivity: firm-level evidence", *Review of Economics and Statistics*, 85(4), 793–808.

Brynjolfsson, E., Hitt, L. M. and S. Yang (2002), "Intangible assets: Computers and Organizational Capital". *Brookings Papers on Economic Activity*, 1: 137–99. doi:10.1353/eca.2002.0003

Cardona, M., Kretschmer, T. and T. Strobel (2013), "ICT and Productivity: Conclusions from the Empirical Literature", *Information Economics and Policy*, 25(3), 109-125. doi:10.1016/j.infoecopol.2012.12.002

Caves, D. W., Christensen, L. R. and E.W. Diewert (1982), "The Economic Theory Index Numbers and the Measurement of Input, Output and Productivity", *Econometric*a, 50 (6), pp. 1393-1414.

Cepeda, G., Cegarra, J. G., and. D. Jiménez, D. (2012), "The Effect of Absorptive Capacity on Innovativeness: Context and Information Systems Capability as Catalysts", *British Journal of Management*, 23(1), pp. 110–129. https://doi.org/10.1111/j.1467-8551.2010.00725.x

Cohen, M. A., and D. Levinthal (1990). "Absorptive Capacity: A New Perspective on Learning and Innovation", *Administrative Science Quarterly*, 35(1), 128–152.

Contreras, F., Aldeanueva, I., Espinosa, J. C., and G. Abid (2021), "Potential and Realized Absorptive Capacity in Colombian Firms: The Mediating Role of the Organizational

Climate for Innovation”. *SAGE Open*, 11(4). https://doi.org/10.1177/21582440211052549

Crescenzi, R. and L. Gagliardi (2018), “The Innovative Performance of Firms in Heterogeneous Environments: The Interplay between External Knowledge and Internal Absorptive Capacities”, *Research Policy*, Vol. 47, Issue 4, pp. 782-795, https://doi.org/10.1016/j.respol.2018.02.006.

Dai, L., Zhang, J. and S. Luo (2022), “Effective R&D Capital and Total Factor Productivity: Evidence using Spatial Panel Data Models”, *Technological Forecasting and Social Change*, Vol. 183, 121886, https://doi.org/10.1016/j.techfore.2022.121886.

Dodgson, M. (1993), “Learning, trust, and technological collaboration”, *Human Relations*, 46(1), pp. 77–95. https://doi.org/10.1177/001872679304600106

Elidjen, E., Pertiw,i A., Mursitama, T.N., and J. T. Beng (2022), “How Potential and Realized Absorptive Capacity Increased Ability to Innovate: the Moderating Role of Structural Ambidexterity”, *VINE Journal of Information and Knowledge Management Systems*, Emerald Publishing Limited, 2059-5891, DOI 10.1108/VJIKMS-12-2021-0298.

Fabiani, S., Schivardi, F., and S. Trento (2005), “ICT Adoption in Italian Manufacturing: Firm-level Evidence”, *Industrial and Corporate Change*, 14(2), 225–249.

Foster-McGregor N., Isaksson A. and F. Kaulich (2016), “Importing, Productivity and Absorptive Capacity in Sub-Saharan African Manufacturing and Services Firms”, *Open Economies Review*, 27, pp. 87–117.

Fulantelli, G., and M. Allegra (2003), “Small company attitude towards ICT based solutions: Some key-elements to improve it”, *Educational Technology & Society*, 6(1), 45–49.

Ghobakhloo, M., Sadegh Sabouri, M., Sai Hong, T., & Zulkifli, N. (2011), “Information Technology Adoption in Small and Medium-sized Enterprises; an Appraisal of Two Decades Literature”, *Interdisciplinary Journal of Research in Business*, 1(7), 53–80.

Giotopoulos I., Kontolaimou A., Korra E. and A. Tsakanikas (2017), “What Drives ICT Adoption by SMEs? Evidence from a Large-Scale Survey in Greece”, *Journal of Business Research*, Vol. 81, pp. 60-69

Girma, S. (2005), “Absorptive Capacity and Productivity Spillovers From FDI: A Threshold Regression Analysis”, *Oxford Bulletin of Economics and Statistics*, 67, 3, 281–306.

Greenan, N. and J. Mairesse (2000), “Computers and productivity in France: Some evidence”, *Economics of Innovation and New Technology*, 9(3): 275–315

Greenley, G. E., Hooley, G. J. and J. M. Rudd (2005). “Market Orientation in a Multiple Stakeholder Orientation Context: Implications for Marketing Capabilities and Assets,” *Journal of Business Research*, 58, 1483–1494.

Hall, B.H., Lotti, F. and J. Mairesse (2013), "Evidence on the Impact of R&D and ICT investments on Innovation and Productivity in Italian Firms", *Economics of Innovation and New Technology*, vol. 22, no. 3, pp. 300-328.

Howell A. (2020), "Relatedness Economies, Absorptive Capacity, and Economic Catch-up: Firm-level Evidence from China", *Industrial and Corporate Change*, Volume 29, Issue 2, pp. 557–575, https://doi.org/10.1093/icc/dtz050

Jansen, J. J. P., Van den Bosch, F. A. J., and H.W. Volberda (2005), "Managing Potential and Realized Absorptive Capacity: How Do Organizational Antecedents Matter?", *Academy of Management Journal*, Vol. 48, n. 6, p. 999–1015.

Joshi, K. D., Chi, L., Datta, A., and S. Han (2010), "Changing the Competitive Landscape: Continuous Innovation Through IT-Enabled Knowledge Capabilities", *Information Systems Research*, 21(3), 472–495. http://www.jstor.org/stable/23015547.

Kaplan, R. S., and D.P. Norton (2008). Mastering the management system. Harvard business review, 86(1), 62.

Kim, M. (2015), "Productivity Spillovers From FDI and the Role of Domestic Firm's Absorptive Capacity in South Korean Manufacturing Industries", *Empirical Economics*, 48, 2, 807–27

Lane, P. J., R. Koka and S. Pathak (2006), "The Reification of Absorptive Capacity: a Critical Review and Rejuvenation of the Construct", *Academy of Management*, 31(4), 833–863.

Leal-Rodríguez, A.L., Ariza-Montes, J.A., Roldán, J.L., A. G. Leal-Millán (2014), "Absorptive Capacity, Innovation and Cultural Barriers: A Conditional Mediation Model, *Journal of Business Research*, Vol. 67, Issue 5, pp. 763-768.

Levinsohn, J. and A. Petrin (2003), "Estimating Production Functions Using Inputs to Control for Unobservables", *Review of Economic Studies*, 70 (2), pp .317-342.

Liao H., Liu X. and C. Wang (2012), "Knowledge Spillovers, Absorptive capacity and Total Factor Productivity in China's Manufacturing Firms", *International Review of Applied Economics*, 26:4, 533-547, DOI: 10.1080/02692171.2011.619970

Liao, J., Welsch, H. and M. Stoica (2003), "Organizational Absorptive Capacity and Responsiveness: an Empirical Investigation of Growth-Oriented SMEs", *Entrepreneurship Theory & Practice*, 28 (2003), pp. 63-85

Limaj, E. and E. W.N. Bernroider (2019), "The Roles of Absorptive Capacity and Cultural Balance for Exploratory and Exploitative Innovation in SMEs", *Journal of Business Research*, Vol. 94, pp. 137-153, https://doi.org/10.1016/j.jbusres.2017.10.052.

Lokshin, B., Belderbos, R. and M. Carree (2008), "The Productivity Effects of Internal and External R&D: Evidence from a Dynamic Panel Data Model", *Oxford Bulletin of*

Economics and Statistics, 70: 399-413. https://doi.org/10.1111/j.1468-0084.2008.00503.x

Marsh I. W., Rincon-Aznar A., Vecchi M. and F. Venturini (2017), "We See ICT Spillovers Everywhere but in the Econometric Evidence: a Reassessment", *Industrial and Corporate Change*, Vol. 26 (6), pp. 067–1088, https://doi.org/10.1093/icc/dtx008

Matusik, S. F. and M. B. Heeley (2005), "Absorptive Capacity in the Software Industry: Identifying Dimensions that Affect Knowledge and Knowledge Creation Activities", *Journal of Management*, 31(4), 549–572.

Min, J.W., Vonortas, N.S. and Y. J. Kim (2019), "Commercialization of Transferred Public Technologies", *Technological Forecasting and Social Change*, Vol. 138, pp. 10-20, https://doi.org/10.1016/j.techfore.2018.10.003.

Minetaki, K. and Omori, T. (2010), "Information and Communication Technology and Productivity in Japan: Regional Level Analysis", Studies in Regional Science, 40(2), pp. 315-325

Mitra, A., Sharma, C. and M.A. Véganzonès-Varoudakis (2016), "Infrastructure, Information and Communication Technology and Firms' Productive Performance of the Indian Manufacturing", Journal of Policy Modeling, Vol. 38, Issue 2, pp. 353 – 371.

Moralles H.F. and R. Moreno (2020), "FDI Productivity Spillovers and Absorptive Capacity in Brazilian firms: A Threshold Regression Analysis", *International Review of Economics & Finance*, Vol. 70, pp. 257-272.

Nedelko, Z., and V. Potočan (2016),"Management Practices Utilization in Organizations–A Comparison between Catching-up and Well-developed Economies", *Management: Journal of Contemporary Management Issues*, 21(Special issue), 1-20.

OECD (2019), OECD Reviews of Digital Transformation: Going Digital in Colombia, OECD Reviews of Digital Transformation, OECD Publishing, Paris, https://doi.org/10.1787/781185b1-en.

Okafor, L.E., Bhattacharya, M. and H. Bloch (2017), "Imported Intermediates, Absorptive Capacity and Productivity: Evidence from Ghanaian Manufacturing Firms", The *World Economy*, 40, pp,369-392. https://doi.org/10.1111/twec.12467

Olley, G. S. and A. Pakes (1996), "The Dynamics of Productivity in the Telecommunications Equipment Industry", *Econometrica*, 64 (6), pp. 1263-1297.

Papaioannou,S.K. and S.P. Dimelis (2007) "Information Technology as a Factor of Economic Development: Evidence from Developed and Developing Countries", Economics of Innovation and New Technology, 16:3, pp. 179-194, DOI: 10.1080/10438590600661889

Powell, W.W., Koput, K.W., and L. Smith-Doerr (1996),“Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology”, *Administrative Science Quarterly*, Vol. 41, No. 1, pp. 116-145.

Raymond, L., Bergeron, F., Croteau, A.-M. and J. St-Pierre (2015), “Developing Absorptive Capacity through e-Business: The Case of International SMEs”, *Journal of Small Business Management*, 53: 75-94. https://doi.org/10.1111/jsbm.12192

Rincon, A., Robinson, C. and M. Vecchi (2005), “The Productivity Impact of E-commerce in the UK, 2001. Evidence from Micro-data”, NIESR Discussion Paper, n. 257.

Rizov, M., Vecchi, M. and J. Domenech (2022), “Going Online: Forecasting the Impact of Websites on Productivity and Market Structure”, Technological Forecasting and Social Change, Volume 184, 121959,https://doi.org/10.1016/j.techfore.2022.121959.

Roth, F., Sen, A, and C. Rammer (2023), “The Role of Intangibles in Firm-level Productivity – Evidence from Germany”, *Industry and Innovation*, 30:2, 263-285, DOI: 10.1080/13662716.2022.2138280.

Rothwell, R. and M. Dodgson (1991), “External Linkages and Innovation in Small and Medium Sized Enterprises”, *R&D Management*, 21 (2), pp. 125–138.

Saraf, N., Liang, H., Xue, Y., and Q. Hu (2013), “How Does Organisational Absorptive Capacity Matter in the Assimilation of Enterprise Information Systems?”, *Information Systems Journal*, 23(3), pp. 245–267. https://doi.org/10.1111/j.1365-2575.2011.00397.x

Schmidt, T. (2010), “Absorptive Capacity - One size Fits all? A firm-level analysis of Absorptive Capacity for Different Kinds of Knowledge”, *Managerial and Decision Economics*, 31(1), 1–18.

Shin, I. (2000), “Use of Information Network and Organizational Productivity: Firm-level Evidence in Korea”, *Economics of Innovation and New Technology*, 9(5), pp. 447-646. doi:10.1080/10438590000000018

Solow, R. M. (1957), “Technical Change and the Aggregate Production Function”, *Review of Economics and Statistics*, 39: 312-20.

Tan, K. S., Chong, S. C., Lin, B., and. U.C. Eze (2010), “Internet-based ICT Adoption among SMEs”, *Journal of Enterprise Information Management*, 23(1), 27–55.

Teece, D.J., Pisano, G. and A. Shuen (1997), “Dynamic Capabilities and Strategic Management”, *Strategic Management Journal*, 18 (7), pp. 509-533

Vonortas, N.S. (2012). Cooperation in Research and Development. vol. 11, Springer Science & Business Media.

Wang, C. L., and P. K. Ahmed (2007). “Dynamic Capabilities: A Review and Research Agenda”, *International Journal of Management Reviews*, 9 (1): pp 31–51.

Wang, Y. (2010), “FDI and Productivity Growth: the Role of Inter-industry Linkages”, *The Canadian Journal of Economics / Revue Canadienne d’Economique*, 43(4), 1243–1272. http://www.jstor.org/stable/40925276

Weerawardena, J. (2003), “The Role of Marketing Capability in Innovation-Based Competitive Strategy”, *Journal of Strategic Marketing* ,11(1), pp. 15–35.

Yasar, M. (2013), “Imported Capital Input, Absorptive Capacity, and Firm Performance: Evidence from Firm-level Data”, *Economic Inquiry*, Vol. 51, Issue 1, pp. 88-100. https://doi.org/10.1111/j.1465-7295.2010.00352.x

Yu, B. (2022), “The Impact of the Internet on Industrial Green Productivity: Evidence from China”, *Technological Forecasting & Social Change*, no. 177, pp. 1-10.

Zahra, S. A., and G. George (2002), “Absorptive Capacity: A Review, Reconceptualization, and Extension”, *Academy of Management Review*, 27(2), 185–203.

Appendix

Table (A.1): Description of firm-level variables utilized at the econometric analysis

Name	Type of variable	Label in regression	Description
TFP**	Nominal		Firm-level TFP is here computed following the three-stage procedure outlined by Olley & Pakes (1996).
ICT investment**	Nominal	*ICT_inv*	General expenditures on informatics, communication and office equipment reported in constant prices
ICT use**	Nominal	*Job_internet*	Percentage share of employees that utilize internet inside the firm to perform their job-related activities
Size**	Nominal	*Size*	Number of workers employed by the establishment
Age**	Nominal	*Age*	Number years by which the establishment has been present on the dataset
R&D cooperation	Binary	*R&D_coop*	Whether the firm received monetary resources (from either domestic or foreign owned entities) in order to cooperate on innovation related activities
Marketing	Binary	*MKT*	Whether the firm executed new commercialization techniques in order to penetrate more market segments
E-communication	Binary	*E_communication*	Whether the firms utilizes either intranet or extranet communication platforms
E-commerce	Binary	*E_commerce*	Whether the firm executes either type of online transaction (sales and procurement)
LAN network	Binary	*LAN_network*	Whether the firm employs LAN networks as a communication platform
Web page	Binary	*Web_page*	Whether the firm has a web page

Note: **All nominal values are here computed using natural logarithms

Table (A.2). Descriptive statistics.

Variable	Mean	Std. Dev	Variance	Skewness	Kurtosis
TFP	-1.05	1.37	1.87	-0.25	4.87
ICT_inv	2.16	1.78	3.16	0.21	3.51
Job_internet	3.22	0.97	0.95	-1.05	4.42
Size	2.89	1.26	1.59	0.07	3.01
Age	1.30	0.72	0.52	-0.54	2.18
R&D_coop	0.00	0.04	0.00	23.50	553.35
MKT	0.06	0.24	0.06	3.60	13.99
E_communication	0.47	0.50	0.25	0.14	1.02
E_commerce	0.62	0.49	0.24	-0.50	1.25
LAN_network	0.94	0.30	0.09	-1.59	9.68
Web_page	0.62	0.49	0.24	-0.50	1.25

Table (A.3). IV regression on productivity determinants: LAN-network

	TFP-OP	TFP-LP	LPROD
ICT_inv	0.444***	0.387***	0.429***
	(0.03)	(0.03)	(0.03)
Size	-0.007	-0.149***	-0.512***
	(0.02)	(0.02)	(0.02)
Age	0.126***	0.066***	0.146***
	(0.02)	(0.02)	(0.02)
LAN_network	0.129***	0.080*	0.112***
	(0.04)	(0.04)	(0.03)
R&D_coop	0.113	-0.040	0.126
	(0.17)	(0.15)	(0.14)
*R&D_coop*LAN_network*	0.715***	0.731***	0.591***
	(0.18)	(0.16)	(0.16)
MKT	0.170	0.148	0.094
	(0.09)	(0.08)	(0.09)
*MKT*LAN_network*	-0.078	-0.094	0.032
	(0.09)	(0.08)	(0.09)
Constant	-1.764***	-6.051***	4.839***
	(0.07)	(0.07)	(0.06)
R^2	0.318	0.180	0.266
Observations	25643	25643	32458

Notes: As described in table (1). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table (A.4). IV regression on productivity determinants: WEB page

	TFP-OP	TFP-LP	LPROD
ICT_inV	0.354***	0.329***	0.332***
	(0.03)	(0.03)	(0.03)
Size	0.036	-0.121***	-0.466***
	(0.02)	(0.02)	(0.02)
Age	0.115***	0.059**	0.134***
	(0.02)	(0.02)	(0.02)
WEB_page	0.303***	0.194***	0.332***
	(0.03)	(0.03)	(0.02)
R&D_coop	0.138	-0.024	0.137
	(0.16)	(0.15)	(0.14)
*R&D_coop*WEB_page*	0.737***	0.740***	0.649***
	(0.17)	(0.16)	(0.16)
MKT	-0.076	-0.101	-0.025
	(0.07)	(0.07)	(0.06)
*MKT*WEB_page*	0.198**	0.182**	0.175**
	(0.07)	(0.07)	(0.07)
constant	-1.778***	-6.063***	4.795***
	(0.06)	(0.05)	(0.05)
R^2	0.340	0.206	0.285
Observations	25643	25643	32458

Notes: As described in table (1). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$