Swiss Leading House

Economics of Education • Firm Behaviour • Training Policies

Working Paper No. 191

Is Technological Change Really Skills-Biased? Firm-level Evidence of the Complementarities between ICT and Workers' Education

Thomas Bolli and Filippo Pusterla

Universität Zürich
IBW – Institut für Betriebswirtschaftslehre

UNIVERSITÄT BERN

Working Paper No. 191

Is Technological Change Really Skills-Biased? Firm-level Evidence of the Complementarities between ICT and Workers' Education

Thomas Bolli and Filippo Pusterla

December 2019

Published as: "Is technological change really skills-biased? Firm-level evidence of the complementarities between ICT and workers' education." *Economics of Innovation and New Technology* (2021). By Thomas Bolli and Filippo Pusterla.

DOI: https://doi.org/10.1080/10438599.2020.1871270

The Swiss Leading House on Economics of Education, Firm Behavior and Training Policies is a Research Program of the Swiss State Secretariat for Education, Research, and Innovation (SERI).

www.economics-of-education.ch

Is Technological Change Really Skills-Biased? Firm-level Evidence of the Complementarities between ICT and Workers' Education*

Thomas Bolli & Filippo Pusterla‡

December 10, 2019

Abstract

This paper extends and refines the concept of ICT-driven skills-biased technological change by disentangling the effects of information technologies (IT) and communication technologies (CT). Guided by the theory that IT and CT differently affect firms' production processes, we investigate the complementarities between these two distinct technologies and workers' levels of education in affecting firms' productivity. Exploiting within-firm variation between 2005-2017, we find that the use of IT—measured as use of business management tools—is particularly beneficial for workers with a tertiary vocational education. In contrast, CT—measured as workers' use of the intranet—is especially complementary to workers with a tertiary academic education. While consistent with the ICT-driven skills-biased technological change hypothesis, our results offer evidence on the necessity for differentiating between the effects of IT and CT on firm productivity when differently educated workers use these technologies.

JEL-Classification: J24, O33

Keywords: skills-biased technological change, information technologies, communication technologies.

*Acknowledgments: This study is partly funded by the Swiss State Secretariat for Education, Research, and Innovation. We are grateful for comments from Uschi Backes-Gellner, Stefan Wolter, and participants at the KOF-Leading House "Economics of Education" joint Workshop, at the 4th CVER Conference, and at the 2nd BIBB Conference on the Economics of Vocational Education and Training.

‡ETH Zurich, KOF Swiss Economic Institute, Leonhardstrasse 21, 8092 Zurich, Switzerland. Corresponding address: pusterla@kof.ethz.ch

1 Introduction

Do information and communication technologies (ICT) affect workers' productivity differently relative to their educational level? The skills-biased technological change hypothesis suggests that new technologies lead to higher productivity, especially for highly educated workers, who possess the necessary skills to use them (see, e.g., Acemoglu, 2002, Hornstein et al., 2005, for a theoretical foundation of skills-biased technological change). The empirical literature confirms the positive relationship between ICT and workers' skills across countries. Researchers specifically emphasize the beneficial effect of ICT for tertiary-educated workers, who represent a proxy for skills (e.g., Michaels et al., 2014). Furthermore, this literature suggests that ICT adoption increases the employment of college-educated workers (Atasoy, 2013), improves their productivity in executing non-routine tasks (Akerman et al., 2015), fosters economic growth through firm entry (Falck, 2017), and increases firm size (DeStefano et al., 2018).

Yet despite the complexity of ICT, most of this research mainly view ICT as a homogeneous input factor when evaluating its impacts on firms' productivity (Draca et al., 2006). Given the lack of accurate indicators of ICT use in the workplace, the majority of this literature considers broadband diffusion a proxy for ICT adoption. However, Bloom et al. (2014) suggest that viewing ICT as a unique measure of technological capital is imprecise, because information technologies (IT) and communication technologies (CT) have different effects. IT makes accessing information less expensive, thereby giving workers more autonomy and a wider span of control. IT thus acts as a decentralizing force that allows workers to handle situations more autonomously. In contrast, CT reduces communication costs and therefore leads to more centralized management. CT thus acts as a centralizing force that shifts decision-making responsibilities from the production level to the management level.

This paper extends and refines the concept of ICT-driven skills-biased technological change by disentangling the effects of IT and CT. We do so by empirically exploring how, given the diverse educational composition of the workforce, these two technologies differently affect firm productivity. We disentangle the complementarities between ICT and workers' education into separate complementarities with IT and CT.

Furthermore, while the economic literature focuses on only two levels of education, we account for heterogeneity in education by also including workers with upper-secondary and tertiary vocational education and training (VET)[1]. Specifically, we subdivide workers into four groups according to their level of education: workers with no post-compulsory education, workers with upper-secondary VET, workers with a tertiary vocational education, and workers with a tertiary academic education. This distinction is particularly valuable for many European countries—such as Austria, Denmark, Germany, and Switzerland—where the majority of workers enter the labor market with a VET background (Hoeckel & Schwartz, 2010).

The analysis relies on the Innovation Survey (hereafter, the Survey) conducted by the KOF Swiss Economics Institute in 2005, 2008, 2011, 2015, and 2017. This paper-based survey, which comprises about 1,500 Swiss firms in each wave, closely resembles the EU Community Innovation Survey. In addition to basic firm characteristics, the Survey's focus on capturing firms' use of ICT provides an ideal data set for analyzing the complementarities between workers' education and ICT. The data includes information on firms' use of business management tools—such as Enterprise Resource Planning (ERP), Supply Chain Management (SCM), Customer Relationship Management (CRM)—and of intranet use among employees. Firm-level information on how workers effectively use ICT offers more granular insight than mere broadband diffusion into the complementary relationship between ICT and skills. Moreover, the Survey also records the percentage of employees who regularly use computerized devices in general.

To assess complementarities, we use quantitative regression analysis. Specifically, we estimate firm-level quadratic production functions, including measures of workers' level of education; use of IT, CT, or ICT; and interaction terms between these two groups of inputs. The panel structure of the data allows us to account for unobserved heterogeneity by exploiting within-firm variation over time. We further control for physical capital and for computer user share. By controlling for computer user share, we account for unobserved omitted variable bias due to other computer-based technologies.

In line with the prediction of the skills-biased technological change hypothesis, we find evidence of the complementary relationship between ICT and workers' level of education. Tertiary-educated workers are more complementary to ICT than workers with a VET degree or workers without post-compulsory education. For IT use, the estimations show that workers with a tertiary vocational education exhibit the largest complementarity. In contrast, workers with a tertiary academic education exhibit the largest degree of complementarity with CT. These re-

[1]We use the terms "upper-secondary VET" and tertiary VET" for education programs that prepare their students for labor market entry in specific occupations. "Occupation" refers to the profession for which a young person receives training and is synonymous with vocation or trade.

sults suggest that, despite the increase in complementarity with ICT at the educational level, the effects of IT and CT differ. These findings reveal the necessity for distinguishing between the effects of IT and CT on firm productivity when differently educated workers use these technologies.

Our paper contributes to three strands of the economic literature. First, we add to the literature analyzing the effects of technological change on the labor market (Bertschek et al., 2015). While most of this research uses computer capital or internet diffusion as a proxy for ICT (primarily due to the lack of accurate indicators of ICT use), we use firm-level information on how workers effectively use ICT.

Second, we contribute to the literature analyzing the effects of new technologies on the organizational structure of firms Bloom et al. (2014). Specifically, we argue that CT and IT have different effects on the degree of centralization, effects that explain why IT and CT affect workers differently according to their level of education. Third, by focusing on a fine-grained distinction of workers' education, we also contribute to the literature on the adaptability of VET-educated workers to technological change (e.g., Hanushek et al., 2017).

In addition to contributing to the scientific literature, our study also adds to the public debate on the relevance of workers' type of education in the use of digital technologies. Our study shows that the degree of complementarity between ICT and workers' education is highly heterogeneous across technologies. Our results suggest that workers with vocational education are not necessarily less able to take advantage of these technologies than workers with an academic education. The heterogeneity in the way that different workers exploit different technologies is potentially highly important not only for firms but also for policy-makers and professional associations.

The rest of the paper is organized as follows. Section 2 presents the conceptual framework of the study and derives the hypotheses. Section 3 describes the data set, and Section 4 explains the estimation strategy. Section 5 presents the results of the analysis. Section 6 concludes.

2 Conceptual Framework and Hypotheses

This section builds the conceptual framework and our hypotheses, both of which are based on two distinct strands of the literature: the complementarity between ICT and skills, and the distinct effects that IT and CT have. First, we review the evidence on the complementarities between workers' education and ICT. Second, we underline the importance of decomposing the effects of ICT into IT and CT, because these two technologies affect firms differently. Third, we combine these two strands of the literature and derive our hypotheses on the complementarity between workers' education and ICT, IT, and CT, respectively.

2.1 The Skills Complementarity of ICT

A growing body of the economic literature analyzes the effect of ICT adoption on labor productivity and wages. Many empirical papers show the complementarity of education and ICT by measuring the effect of broadband internet diffusion on labor market outcomes (see Bertschek et al. 2015, for a review). This literature suggests that broadband adoption increases the employment of college-educated workers (Atasoy, 2013), improves the productivity of highly skilled workers performing non-routine tasks (Akerman et al., 2015), fosters economic growth through firm entry (Falck, 2017), and has a generally positive effect on firm size because it increases total revenues and the number of employees (DeStefano et al., 2018). As to possible heterogeneous effects across industries, Stockinger (2019) finds that broadband adoption in Germany leads to negative employment effects in manufacturing but to positive ones in the service industries.

By exploiting the exogenous variation in the availability of broadband, these studies largely contribute to explaining the causal relationship between internet diffusion and workers' skills. Nonetheless, the main limitation of this literature lies in its using broadband diffusion as a proxy for ICT adoption. The reason for their using broadband diffusion in this way is usually due to the lack of accurate workplace measures of ICT use (Draca et al., 2006).

An exception is Falk & Biagi (2017), who analyze the relationship between the relative demand for highly educated workers and ICT usage. Their approach consists of using micro-aggregated data at both the industry and firm-size levels on the adoption of enterprise resource planning system and e-commerce. Using firm-level panel data covering ten European countries, they find that the adoption of ERP has a positive employment effect in manufacturing, while e-commerce has a positive impact in the service industries. In contrast, for e-sale activities, e-buying activities, and the percentage of employees with broadband access, they find no significant effect on employment.

Although broadband access might be appropriate at the macro-level, and although industry-level micro-aggregated data can offer interesting insights into differences across industries, only firm-level information on how workers effectively use ICT can provide direct evidence on the complementary relationship between ICT and skills. However, studies exploiting firm-level information on the type of ICT use are scarce.

Pantea et al. (2017) use a micro-level firm-employee linked data set combining information on ICT use with indicators of firms' economic characteristics. Specifically, they measure ICT not only as broadband intensity but also as mobile internet intensity and intensity of e-sales. This data allows them to compare groups of industries across seven European countries. Their results suggest that ICT use has a statistically insignificant substitution effect on labor. More specifically, their finding suggests that increased within-firm use of ICT does not reduce the total number of workers employed by firms. However, by focusing on the total number of employees, they do not investigate the effect of ICT adoption by group of workers with a specific education.

2.2 Disentangling ICT into IT and CT

The economic literature traditionally models ICT as a homogeneous input factor (Draca et al., 2006), with many researchers considering ICT a single production factor when evaluating its impacts on firms in particular or on the economy as a whole. However, Bloom et al. (2014) emphasize that considering ICT as a single measure of technology is imprecise, because IT and CT have different effects.

2.2.1 The Complementarity between Workers' Education and IT

Given that IT makes accessing information less expensive and therefore gives workers more autonomy and a wider span of control, IT acts as a decentralizing force that allows workers to handle situations more autonomously. The increasing availability of firm-level data on the adoption of different types of IT has led to more fine-grained research on the effect of IT and the extent of the complementarities with workers' level of education. The information systems literature views the use of business management tools such as ERP, CRM, and SCM as the main measure of firms' adoption of IT (e.g. Banker et al. 2006, Heim & Peng 2010).

ERP denotes the software sustaining day-to-day business activities and supporting the decision-making process (Ruivo et al., 2014). It improves coordination between different units of the firm, increases efficiency in the business process, and decreases costs of coordination (Hitt et al. 2002, Nicolaou & Bhattacharya 2006). CRM is a system that brings together not only firms and their customers but also other resources and organizational capabilities, to ensure the exchange of data and knowledge (Alshawi et al. 2011, Payne & Frow 2006). SCM denotes the process of providing better integration of production and distribution systems, and developing strong ties between suppliers and customers (Ince et al., 2013). It focuses on information management tools that integrate procurement, operations, and logistics (Kovács & Paganelli, 2003), tools that act as a decentralizing force allowing workers to handle situations more autonomously.

Stucki & Wochner (2018) apply firm-level data on the use of IT (measured as the use of ERP, CRM, and SCM) and firm organization. Their results suggest that IT increases firm productivity when combined with organizational practices that give workers greater autonomy.

For the complementarity of IT with workers' skills, Drucker (1988) hypothesizes that the rise of IT could lead to a flatter organizational structure mainly comprising autonomous specialists. Bresnahan et al. (2002) empirically show that IT use is positively associated with more skilled labor, because IT allows greater autonomy for skilled workers. Arvanitis (2005) tests the extent of the complementarity between IT use and human capital by using the 1999 cross-section of the survey data that we use in this study. Arvanitis (2005) defines human capital as the percentage of VET employees with tertiary-level vocational education. His results suggest that IT is complementary with human capital, and that workers with a tertiary vocational education are also complementary with IT. In Switzerland, we thus expect that IT adoption, which implies greater autonomy and increased decentralization, positively and similarly affects tertiary-educated workers, both vocational and academic.

2.2.2 The Complementarity between Workers' Education and CT

The information systems literature views CT as electronic systems that allow individuals to communicate with other individuals or groups (Huang et al., 2012), particularly in terms of exchanging knowledge and coordinating activities. By reducing communication costs, CT leads to more centralized management (Bloom et al., 2014), thereby acting as a centralizing force that shifts decision-making responsibilities from the production level to the management level.

Examples of CT are telephone, fax, email, and video conferencing. Bloom et al. (2014) emphasize that the key technological innovation since the late 1990s has been the introduction of the intranet, which facilitates knowledge sharing among workers within a single firm. By integrating information into a single system, the intranet enables employees to find, share, and communicate information relevant to their jobs (Boersma & Kingma, 2008).

As to the complementarity of CT with workers skills, a number of studies view CT as a centralizing force, creating workers' dependency on a few "superstars" (Rosen 1981, Kim &

Brynjolfsson 2009, Brynjolfsson et al. 2010). From a firm's organizational perspective, CT reduces the costs of decision-making, thereby leading to more centralized management (Gurbaxani & Whang, 1991). The reduction in communication costs following the introduction of the intranet allows managers to less expensively refer decisions to corporate officers (Bloom et al., 2010).

Garicano (2000) observes that the less expensive transmission of knowledge increases the importance of problem-solvers, who can enlarge their span of control over a larger number of workers while simultaneously reducing the decision-making scope of production workers. CT decreases communication costs and makes supervisor consultation more efficient, thereby making supervisors more productive.

Using data covering American and European manufacturing firms, Bloom et al. (2014) investigate the effect of CT on worker autonomy. They find that CT—measured by the extent of intranet use—decreases workers' autonomy and leads to more centralization. In line with Bloom et al. (2014), we hypothesize that CT is especially complementary with highly educated workers, who conduct managerial tasks and therefore profit the most from task centralization.

2.3 Hypotheses

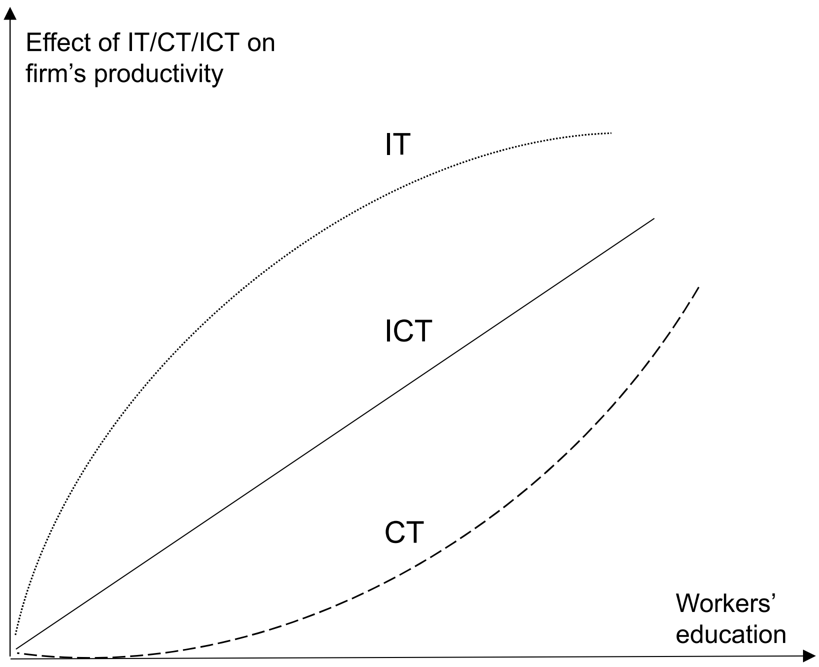
Drawing on our conceptual framework and the empirical literature just discussed, we develop our research hypotheses. Figure 1 graphically represents our hypotheses on the complementarity between workers' education and IT, CT, and ICT, respectively. The y-axis reports the effects of these technologies on firms' productivity, while the x-axis reports workers' levels of education.

The solid line represents the complementary effect of ICT and workers' education on firm's productivity. In line with the skills-biased technological change hypothesis, the upward sloping line indicates that the effect of ICT increases with workers' education. We thus hypothesize as follows:

H1: The complementarity between *ICT* and workers' education in affecting firms' productivity is positive.

The dotted line in Figure 1 represents the complementary effect of IT and workers' education on firms' productivity. This concave line suggests that although the complementarity between the use of IT and workers' education is increasing, the increase is slowing. Indeed, IT makes ac-

Figure 1: Graphical representation of the hypotheses



cessing information cheaper and therefore induces decentralization. Moreover, decentralization strongly increases the productivity of workers in the middle of the education distribution, while highly educated workers profit from the effect of IT only slightly more. Given these patterns, we thus hypothesize as follows:

H2: The complementarity between IT and workers' education in affecting firms' productivity increases with education, but with a diminishing increase.

Finally, the dashed line in Figure 1 represents the complementary effect of CT and workers' education on firms' productivity. The relationship follows an exponential pattern, with CT acting as a centralizing force, because it reduces communication costs and thus shifts decision-making responsibilities from the production to the management level. Therefore, highly educated workers profit the most from the use of CT. Conversely, CT has almost no effect on productivity for poorly educated workers.

We thus hypothesize as follows:

H3: The complementarity between CT and workers' education in affecting firms' productivity increases exponentially with education.

3 Data and description of variables

The data used in this paper stems from the KOF Innovation Survey, conducted by the KOF Swiss Economic Institute from 2005 through 2017. The survey was conducted every three years between 2005-2011 and every second year since 2015. The response rates are about 38.7% (2005), 36.1% (2008), 35.9% (2011), 30.0% (2015), and 26.8% (2017), which correspond to about 1,500 firm observations per wave. These response rates are satisfactory, given that the questionnaire[2]. is relatively demanding and time-consuming. The surveys are based on stratified random samples drawn from the Swiss business census for firms with more than five employees.

The data were pooled to a data set of 6,690 observations. This sample includes all firms having information on workers' level of education and workers' use of ICT technologies. The data set also contains information on financial variables, such as firms' total value added and the level of gross investments. Table 1 reports the description of the main variables used for the empirical analysis. Table A1 in the Appendix reports the summary statistics of these variables.

To investigate the complementarity effects between ICT and workers' level of educational in affecting firms' productivity, we focus on two main groups of variables: First, the survey asks about the total number of workers and the percentage of each educational group. We calculate the number of workers according to the highest level of education achieved to create four groups: "Lower" educated workers have no post-compulsory education, "trained" workers have an upper-secondary VET education, "advanced" workers have a tertiary vocational education, and "academic" workers have a tertiary academic education. Given the structure of the Swiss education system[3], only few workers end up in the labor force with an academic upper-secondary diploma as their highest degree (i.e., most continue to tertiary academic education). For this reason, the survey does not explicitly ask for the percentage of workers limited to this kind of education. All four groups of workers have a minimum value of zero[4], meaning that no firm necessarily has all four groups of workers.

[2]The questionnaires, which closely resembles the EU Community Innovation Survey, are available online in all Swiss national languages (German, French, and Italian) at www.kof.ethz.ch/en/surveys/structural-surveys/innovation-survey/

[3]The Swiss education system has both an academic and a vocational track at the upper-secondary and tertiary levels. After finishing compulsory education, the vast majority of Swiss youngsters starts a vocational education (either dual-VET or full-time VET-school) and receive a nationally recognized VET-diploma that gives them access to vocational institutions at the tertiary level: Universities of Applied Sciences, Professional Education and Training Colleges, and (Advanced) Federal Professional Education and Training Exams. In contrast, the proportion of pupils opting for general education courses at upper-secondary level is relatively small (about 20%). See Wolter et al. (2018) for a detailed description of the Swiss education system.

[4]See summary statistics in Table A1.

Table 1: Variable descriptions

Dependent variable	
Value added	Total value added, logarithm.
Independent variables	
Capital	
Capital	Firm's total capital stock calculated using the perpetual inventory methodology, logarithm
Workforce education	
Lower	Total number of untrained employees and dual VET students in a firm, logarithm.
Trained	Total number of employees in a firm with an upper secondary VET education, logarithm.
Advanced	Total number of employees in a firm with a tertiary vocational education (including university of applied sciences), logarithm.
Academic	Total number of employees in a firm with a conventional university (academic) tertiary education, logarithm.
ICT variables	
IT	IT software used by the firm. Mean of three dummy variables: (1) Enterprise Resource Planning (ERP), (2) Customer Relationship Management (CRM), (3) Supply Chain Management (SCM).
CT	Percentage of employees that regularly use the intranet. Transformation of a 6-level ordinal variable (level 1: 0%; level 2: 1–20%; level 3: 21–40%; level 4: 41–6%; level 5: 61–80%; level 6: 81–100%) to point measures by taking the average between the two ends of the respective intervals.
ICT	Overall measure of ICT. Mean of IT and CT variables.
Control variable	
Computer user share	Percentage of employees that regularly use computerized devices. Transformation of 6-level ordinal variable (level 1: 0%; level 2: 1–20%; level 3: 21–40%; level 4: 41–6%; level 5: 61–80%; level 6: 81–100%) to point measures by taking the average between the two ends of the respective intervals.

For the average composition of the workforce, the largest group is *Trained* workers (49%), followed by *Lower* (25%) and *Advanced* workers (16%). *Academic* workers (10%) constitute the smallest group in our sample. Because all of these labor variables enter the estimations in logs, we add one to all variables before taking logarithms. By so doing, we avoid generating variables with missing values for all firms that do not have employees within one of these four educational groups.

Second, we define the measures of firms' use of CT and IT. The CT measure is based on a 6-level ordinal variable that measures the percentage of employees who regularly use the intranet. The IT measure is based on three binary variables reporting firms' use of ERP, CRM, and SCM software, respectively. Measuring IT by aggregating these three technologies is supported by the computer system literature, which suggests complementarity among these practices. For example, Ruivo et al. (2014) suggest that ERP and CRM have an integrative value in exploiting the values of IT.

We take the mean of the standardized values of ERP, CRM, and SCM before aggregating them into the IT measure[5]. To deal with potential differences in the importance of these three different technologies, we further standardize all variables with zero-mean and unit-variance. To test our first hypothesis of the aggregate effect of ICT, we create a measure that consists of the mean between the IT and CT measures.

Computer user share reports the percentage of employees who regularly use computerized devices. This variable serves as a control variable for the use of other computer-based technologies. Therefore, we account for potential unobserved omitted variable bias due to computer-based technologies different from ICT.

4 Empirical strategy

To assess complementarities among workers' level of education and ICT, we use quantitative regression analysis. We follow the interaction approach (Ennen & Richter, 2010) and estimate firm-level quadratic production functions that allow us to identify complementarities among inputs.

We allow productivity to be determined by firms' capital stock K, the number of workers L with education level p, and firms' adoption of IT, CT, or ICT, respectively, which is summarized by $Tech$. The factors K, L_p and $Tech$ enter in the production function both linearly and as a quadratic term. L_p also enters the estimation as an interaction term with Tech. Linear and quadratic terms account for economies of scale, while the interaction terms allow us to identify complementarities between $Tech$ and workers' level of education.

We define the production function as follows:

$$\begin{aligned} VA_{it} = \alpha + \beta_k\ K_{it} + \gamma_k\ K_{it}^2 + \sum_{p=1}^{4} \zeta_{l,p}\ L_{p,it} + \sum_{p=1}^{4} \eta_{l,p}\ L_{p,it}^2 + \theta\ Tech_{it} + \vartheta\ Tech_{it}^2 \\ + \sum_{p=1}^{4} \lambda_p\ L_{p,it}\ Tech_{it} + \psi\ CompShare_{it} + \omega_i + \mu_t + \epsilon_{it} \end{aligned} \tag{1}$$

[5]See Bresnahan et al. (2002) for a related procedure.

where VA_{it} is the log of total value added of firm i at time t. K_{it} is the log of capital stock, while $L_{p,it}$ is the log of the number of workers with education p. $Tech_{it}$ represents the extent of adoption of IT, CT, or ICT by firm i at time t. $CompShare_{it}$ represents the share of employees that regularly uses computerized devices in firm i at time t. By controlling for computer user share, we account for unobserved omitted variable bias due to other computer-based technologies. ω_i and μ_t introduce firm and time fixed effects, respectively. ϵ_{it} is the error term, clustered at the firm level. The inclusion of firm fixed effects in equation 1 prevents possible bias due to time-invariant unobserved heterogeneity.

The coefficients of interest are λ for each of the four educational groups. We identify potential complementarities between workers' level of education and IT, CT, or ICT, respectively, by comparing the pattern of the various interaction terms of the educational variables with $Tech$. If the size of the coefficients of the interaction terms increases with the level of education, then complementarities with $Tech$ exist. However, if the size of the coefficients for the four education groups is very similar, then complementarities between education and IT, CT, or ICT, respectively, in affecting firms' productivity do not exist. Finally, if the size of the coefficients of the interaction terms decreases with the level of education, then substitutability with $Tech$ exists.

5 Estimation Results

Table 2 reports the results based on the estimation of equation 1 for the three ICT measures of interest: ICT in column (1), IT in column (2), and CT in column (3). In column (4) we include both the IT and CT measures. All estimations include firm and year fixed effects, and control for computer user share. The upper part of the table reports the coefficients of capital and labor. The middle part shows the coefficients of the ICT variables and the interaction terms between the ICT variables and the four labor components. The bottom part reports the t-tests of pairwise equality between the coefficients of the interaction terms. The comparison between the sizes of these interaction terms represents our measure of complementarity.

We focus first on the upper part of Table 2. The coefficients for $Capital$ and $Capital^2$ are stable across estimations, with values of about -0.16 and 0.013, respectively. These values suggest increasing marginal return with respect to the input capital. The linear coefficients for labor, which we subdivide into four educational groups ($Lower$, $Trained$, $Advanced$, and $Academic$

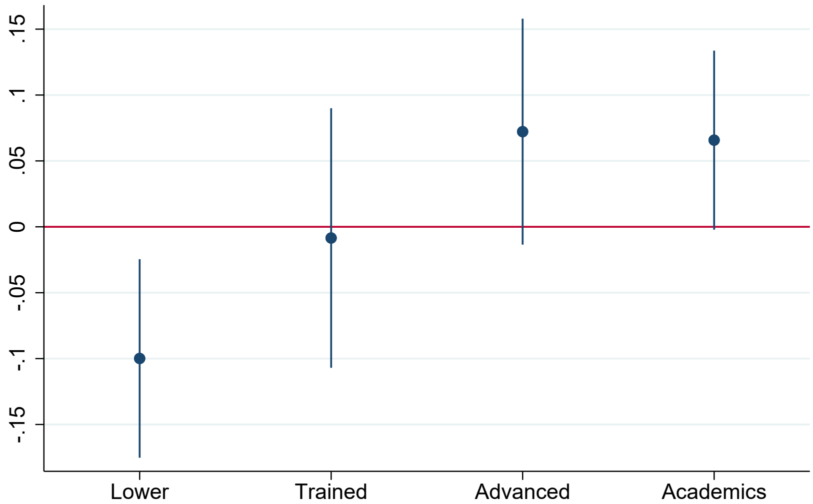
Table 2: Results

	(1) ICT	(2) IT	(3) CT	(4) IT & CT
Capital	-0.164***	-0.159***	-0.164***	-0.158***
	(0.0533)	(0.0534)	(0.0533)	(0.0532)
Capital^2	0.0134***	0.0130***	0.0134***	0.0130***
	(0.00403)	(0.00405)	(0.00402)	(0.00403)
Lower	0.0494	0.0444	0.0190	0.0385
	(0.0372)	(0.0358)	(0.0376)	(0.0372)
Trained	0.205***	0.204***	0.209***	0.207***
	(0.0531)	(0.0558)	(0.0541)	(0.0561)
Advanced	0.157***	0.165***	0.164***	0.159***
	(0.0343)	(0.0351)	(0.0344)	(0.0342)
Academic	0.0423*	0.0589**	0.0433*	0.0481*
	(0.0250)	(0.0261)	(0.0238)	(0.0254)
Lower^2	0.0304***	0.0323***	0.0292***	0.0328***
	(0.00689)	(0.00718)	(0.00678)	(0.00719)
Trained^2	0.00924	0.00753	0.00903	0.00892
	(0.00867)	(0.00950)	(0.00828)	(0.00919)
Advanced^2	-0.0169**	-0.0194**	-0.0131*	-0.0180**
	(0.00767)	(0.00784)	(0.00710)	(0.00774)
Academic^2	-0.00121	0.00260	-0.00170	-0.00251
	(0.00686)	(0.00648)	(0.00680)	(0.00686)
ICT variable	0.0152			
	(0.144)			
ICT variable^2	0.0768			
	(0.137)			
Lower * ICT	-0.0999***			
	(0.0384)			
Trained * ICT	-0.00849			
	(0.0502)			
Advanced * ICT	0.0722*			
	(0.0437)			
Academic * ICT	0.0658*			
	(0.0346)			
IT variable		0.118		0.101
		(0.129)		(0.130)
IT variable^2		0.00370		0.000848
		(0.0890)		(0.0889)
Lower * IT		-0.114***		-0.116***
		(0.0341)		(0.0359)
Trained * IT		0.0162		0.0237
		(0.0472)		(0.0485)
Advanced * IT		0.0802**		0.0833**
		(0.0369)		(0.0369)
Academic * IT		0.00211		-0.00629
		(0.0238)		(0.0241)
CT variable			-0.0550	-0.0276
			(0.124)	(0.123)
CT variable^2			0.0403	0.0224
			(0.114)	(0.113)
Lower * CT			-0.00517	0.0130
			(0.0325)	(0.0336)
Trained * CT			-0.0258	-0.0353
			(0.0340)	(0.0352)
Advanced * CT			0.0117	-0.00353
			(0.0288)	(0.0284)
Academic * CT			0.0721***	0.0755***
			(0.0249)	(0.0248)
Computer user share	-0.0574	-0.0364	-0.0547	-0.0512
	(0.0545)	(0.0511)	(0.0590)	(0.0583)
Firm fixed effects	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓
N	6690	6690	6690	6690
Test for $\beta_{Lower*ICT} = \beta_{Trained*ICT}$	0.233			
Test for $\beta_{Lower*ICT} = \beta_{Advanced*ICT}$	0.0046***			
Test for $\beta_{Lower*ICT} = \beta_{Academic*ICT}$	0.0024***			
Test for $\beta_{Trained*ICT} = \beta_{Advanced*ICT}$	0.300			
Test for $\beta_{Trained*ICT} = \beta_{Academic*ICT}$	0.229			
Test for $\beta_{Advanced*ICT} = \beta_{Academic*ICT}$	0.917			
Test for $\beta_{Lower*IT} = \beta_{Trained*IT}$		0.0673*		0.0620*
Test for $\beta_{Lower*IT} = \beta_{Advanced*IT}$		0.0003***		0.0003***
Test for $\beta_{Lower*IT} = \beta_{Academic*IT}$		0.0049***		0.0094***
Test for $\beta_{Trained*IT} = \beta_{Advanced*IT}$		0.374		0.406
Test for $\beta_{Trained*IT} = \beta_{Academic*IT}$		0.796		0.594
Test for $\beta_{Advanced*IT} = \beta_{Academic*IT}$		0.123		0.0802*
Test for $\beta_{Lower*CT} = \beta_{Trained*CT}$			0.728	0.437
Test for $\beta_{Lower*CT} = \beta_{Advanced*CT}$			0.720	0.729
Test for $\beta_{Lower*CT} = \beta_{Academic*CT}$			0.0468**	0.109
Test for $\beta_{Trained*CT} = \beta_{Advanced*CT}$			0.447	0.519
Test for $\beta_{Trained*CT} = \beta_{Academic*CT}$			0.0329**	0.0199**
Test for $\beta_{Advanced*CT} = \beta_{Academic*CT}$			0.161	0.0633*

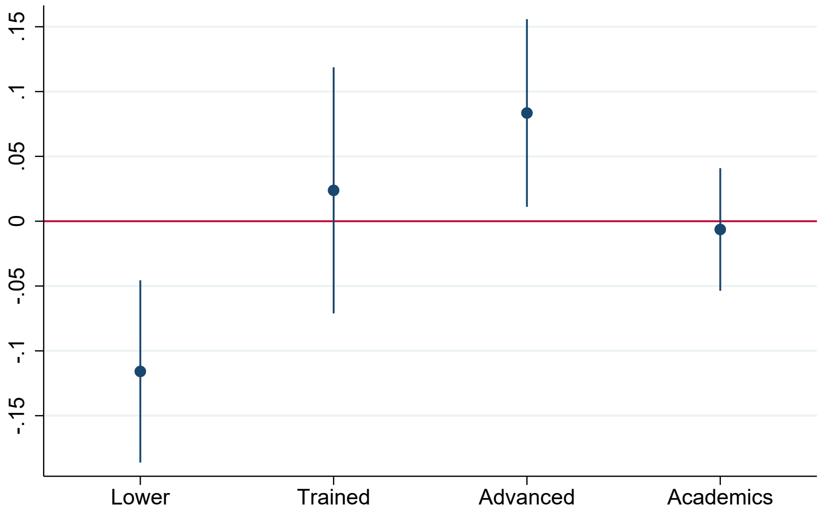
Notes: Firm-level production functions estimated with OLS. Dependent variable is the log of total value added. Capital, Lower, Trained, Advanced, and Academic are in logs. ICT variables are standardized with mean equal to 0 and standard deviation equal 1. Standard errors clustered at firm level in parentheses. * p<0.10, ** p<0.05, *** p<0.01. The bottom part of the table reports the p-values of the t-tests for pairwise equality of the interaction terms.

Figure 2: Coefficients of the interaction terms between workers' education and and IT, CT, or ICT, respectively

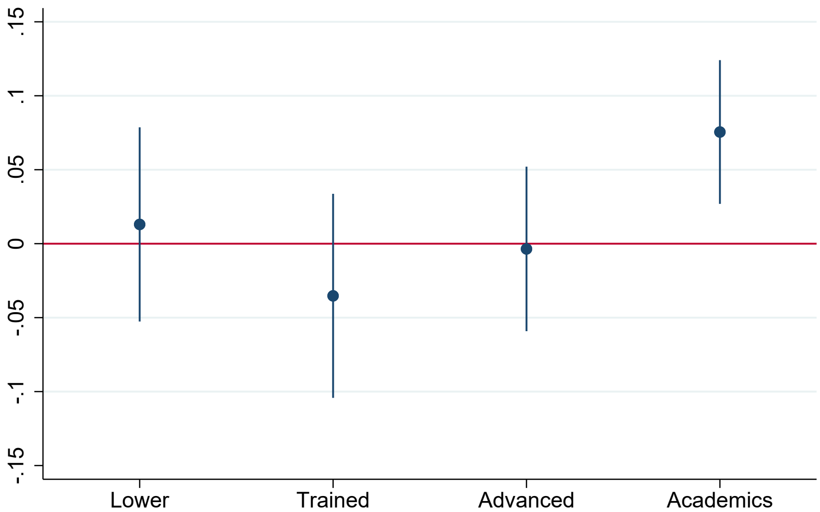
(a) ICT



(b) IT



(c) CT



Notes: The graphs report the coefficients and the corresponding confidence intervals (95%) of the interaction terms between the four educational groups of workers and the three ICT variables presented in the middle part of Table 2: ICT (2a), IT (2b), and CT (2c).

workers), are all positive across estimations. The linear coefficient for *Lower* workers is small and statistically not different from zero. The quadratic term for workers in this education group is positive and large. These two patterns together suggest some possible increasing marginal return of *Lower* educated workers.

In contrast, for the groups of *Trained* workers, the linear coefficient is positive and large, while the quadratic term is not statistically different from zero. These patterns suggest that *Trained* workers contribute mainly in a positive linear way to firms' productivity. The coefficient of the linear term for *Advanced* workers is also positive, while the coefficient of the quadratic term is negative. These patterns suggest a decreasing marginal effect of the *Advanced* workers in affecting firms' productivity. Finally, the coefficients of the linear term of *Academic* workers are positive but small. However, the quadratic term for *Academic* workers is not statistically different from zero. These patterns suggest that *Academic* workers contribute relatively less to firms' productivity, likely because this group of workers is the smallest within the workforce (see Table A1).

We now focus on the middle part of Table 2, reporting the coefficients for the variables accounting for IT, CT, or ICT, respectively, and the corresponding interaction terms with the labor components. Starting with column (1), the interaction terms between ICT and the four education groups allows us to test our first hypothesis. In this column, we present the estimations of the production functions including ICT as $Tech$ variable. The linear and quadratic coefficients of ICT are positive but not statistically significant, suggesting no general effect of ICT on firms' productivity. The coefficients of the interaction terms between ICT and workers' education represent our main factor of interest. To facilitate the comparison of these four coefficients, we also report them graphically in Figure 2a. The coefficient for $Lower * ICT$ is negative, the one for $Trained{*}ICT$ is close to zero, while the coefficients for $Advanced{*}ICT$ and $Academic{*}ICT$ are both positive and statistically different from zero. By comparing these coefficients, we thus observe that the complementarity between ICT and workers' level of education increases with education.

Graphically, we easily observe this increasing pattern in complementarity, which is in line with hypothesis H1 of skills-biased technological change. Importantly, as the t-tests of pairwise equality reported in the bottom part of Table 2 confirm, the coefficients for $Advanced * ICT$ and $Academic * ICT$ are not statistically different. This finding suggests that tertiary-educated workers—both vocational and academic—show similar levels of complementarity with ICT.

The middle part of column (2) presents the results of the production function when we interact workers' education with IT. The baseline effect of the IT is positive, albeit not statistically significant. Indeed, both the linear coefficient for IT as the quadratic one IT^2 are positive, but not statistically different from zero. The coefficient of the interaction terms $Lower * IT$ suggests low complementarity between these two inputs. The t-tests of pairwise equality reported in the bottom part of Table 2 confirm that the coefficient of this interaction term is statistically different from all other interaction terms. The coefficients for the interaction term between IT and both $Trained$ and $Academic$ workers are close to zero, while the coefficient for the interaction term $Advanced * IT$ suggests large complementarity between $Advanced$ workers and IT.

Figure 2b graphically presents these four coefficients and the corresponding 95% confidence intervals. Even though the coefficient for $Advanced$ workers is not statistically different from that of $Academic$ workers, we see an indication of diminishing complementarity between workers' level of education and IT. This finding supports our hypothesis H2.

The middle part of column (3) presents the coefficients of the production function when we interact workers' education with CT. The coefficient for both CT and CT^2 are not statistically significant from zero. This insignificance indicates the absence of a clear baseline effect of CT on productivity. Indeed, as the coefficients of the interaction terms show, CT affects productivity only when combined with a given group of workers. More specifically, as the positive coefficient of the interaction term suggests, CT is complementary with $Academic$ workers. In contrast, all other interaction terms show coefficients not statistically different from zero. The t-tests of pairwise equality reported in the bottom part of Table 2 confirm that the coefficient for $Academic * CT$ is statistically different from that of $Lower * CT$ and $Trained * CT$ at the 5% level, while only slightly not statistically different from that of $Advanced * CT$.

Figure 2c graphically presents these four coefficients and the corresponding 95% confidence intervals. This pattern supports our hypothesis H3 of exponentially increasing complementarity between CT and workers' level of education.

Finally, the middle part of column (4) presents the results of the production function when including both IT and CT measures. Including both technologies allows us to test the robustness of the results presented thus far. One issue is that estimating IT and CT separately in columns (2) and (3) might have mixed up the two effects. We therefore include both measures in the same estimation. Comparing the coefficients of the interaction terms in column (4) with those in columns (2) and (3) shows that the effects of IT and CT are very stable. This finding supports the idea that complementarities between workers education and IT or CT are different.

6 Conclusion

This paper extends the concept of ICT-driven skills-biased technological change by analyzing the complementarities between ICT and workers' level of education in affecting firms' productivity. We add to the literature on the impact of technological change on the labor market by disentangling the effects of ICT into those of IT and CT. This differentiation is motivated by Bloom et al. (2014), who argue that IT and CT differently affect firms' production process. IT makes accessing information less expensive, thereby giving workers more autonomy and a wider span of control. IT thus acts as a decentralizing force that allows workers to handle situations more autonomously. In contrast, CT reduces communication costs and therefore leads to more centralized management, thereby acting as a centralizing force that shifts decision-making responsibilities from the production level to that of management.

We also contribute to the literature on skills-biased technological change by differentiating among four types of workers' education, whereas most studies focus only the two groups of high- and low-skilled workers. In addition to those two groups, our novel analysis includes workers with an upper-secondary vocational education and workers with a tertiary vocational education. The addition of these two educational groups is highly valuable for countries with a large vocationally educated workforce, such as Austria, Denmark, Germany, and Switzerland.

Using Swiss firm-level panel data covering the period 2005-2017, we estimate quadratic production functions including four groups of workers classified according to the highest level of education achieved and our measures of ICT, IT, and CT. We identify potential complementarities between workers' level of education and IT, CT, or ICT, respectively, by comparing the pattern of the various interaction terms of the educational variables with these technologies.

Our results indicate that the use of IT (measured as the use of ERP, CRM, and SCM) is particularly complementary with workers having a tertiary vocational education. In contrast, CT (measured as workers' use of the intranet) is particularly complementary with workers having a tertiary academic education. Consequently, ICT—the combination of IT and CT—is complementary with both vocational and academic education. While consistent with the ICT-driven skills-biased technological change hypothesis, our results reveal the necessity for distinguishing between the effects of IT and CT when differently educated workers use these technologies.

This paper has several limitations that open the door to future research. First, our estimations are based on survey data, which might suffer from measurement errors. Future research using administrative data could avoid random and systematic measurement errors. Second, the structure of the surveys do not allow us to have worker-level information, such as age, gender, labor market experience, or skills mismatch. Differentiating among these characteristics would allow future research to refine the degree of complementarity. Third, a crucial open question is whether the adoption of ICT has an effect on firms' organizational structure. Indeed, a large body of literature highlights the existence of complementarities between firms' organizational practices and ICT. Future research should therefore examine complementarities among education, organization, and ICT within the same research framework.

References

Acemoglu, D. (2002). Technical change, inequality, and the labor market. *Journal of economic literature*, *40*(1), 7–72.

Akerman, A., Gaarder, I., & Mogstad, M. (2015). The skill complementarity of broadband internet. *The Quarterly Journal of Economics*, *130*(4), 1781–1824.

Alshawi, S., Missi, F., & Irani, Z. (2011). Organisational, technical and data quality factors in CRM adoption – SMEs perspective. *Industrial Marketing Management*, *40*(3), 376–383.

Arvanitis, S. (2005). Computerization, workplace organization, skilled labour and firm productivity: Evidence for the swiss business sector. *Economics of innovation and new technology*, *14*(4), 225–249.

Atasoy, H. (2013). The effects of broadband internet expansion on labor market outcomes. *ILR Review*, *66*(2), 315–345.

Banker, R. D., Bardhan, I. R., Chang, H., & Lin, S. (2006). Plant information systems, manufacturing capabilities, and plant performance. *MIS quarterly*, 315–337.

Bertschek, I., Briglauer, W., Hüschelrath, K., Kauf, B., & Niebel, T. (2015). The economic impacts of broadband internet: A survey. *Review of Network Economics*, *14*(4), 201–227.

Bloom, N., Garicano, L., Sadun, R., & Van Reenen, J. (2014). The distinct effects of information technology and communication technology on firm organization. *Management Science*, *60*(12), 2859–2885.

Bloom, N., Sadun, R., & Van Reenen, J. (2010). Recent advances in the empirics of organizational economics. *Annu. Rev. Econ.*, *2*(1), 105–137.

Boersma, K. & Kingma, S. (2008). Intranet and organizational learning. In *Knowledge Management: Concepts, Methodologies, Tools, and Applications* (pp. 1065–1072). IGI Global.

Bresnahan, T. F., Brynjolfsson, E., & Hitt, L. M. (2002). Information technology, workplace organization, and the demand for skilled labor: Firm-level evidence. *The Quarterly Journal of Economics*, *117*(1), 339–376.

Brynjolfsson, E., Hu, Y., & Smith, M. D. (2010). Research commentary: Long tails vs. superstars: The effect of information technology on product variety and sales concentration patterns. *Information Systems Research*, 736–747.

DeStefano, T., Kneller, R., & Timmis, J. (2018). Broadband infrastructure, ICT use and firm performance: Evidence forUK firms. *Journal of Economic Behavior & Organization*, *155*, 110–139.

Draca, M., Sadun, R., & Van Reenen, J. (2006). Productivity and ICT: A Review of the Evidence.

Drucker, P. F. (1988). The coming of the new organization.

Ennen, E. & Richter, A. (2010). The whole is more than the sum of its parts-or is it? A review of the empirical literature on complementarities in organizations. *Journal of Management*, *36*(1), 207–233.

Falck, O. (2017). Does broadband infrastructure boost employment? *IZA World of Labor*.

Falk, M. & Biagi, F. (2017). Relative demand for highly skilled workers and use of different ICT technologies. *Applied Economics*, *49*(9), 903–914.

Garicano, L. (2000). Hierarchies and the organization of knowledge in production. *Journal of political economy*, *108*(5), 874–904.

Gurbaxani, V. & Whang, S. (1991). The impact of information systems on organizations and markets. *Communications of the ACM*, *34*(1), 59–73.

Hanushek, E. A., Schwerdt, G., Woessmann, L., & Zhang, L. (2017). General Education, Vocational Education, and Labor-Market Outcomes over the Lifecycle. *Journal of Human Resources*, *52*(1), 48–87.

Heim, G. R. & Peng, D. X. (2010). The impact of information technology use on plant structure, practices, and performance: an exploratory study. *Journal of Operations Management*, *28*(2), 144–162.

Hitt, L. M., Wu, D., & Zhou, X. (2002). Investment in enterprise resource planning: Business impact and productivity measures. *Journal of management information systems*, *19*(1), 71–98.

Hoeckel, K. & Schwartz, R. (2010). Learning for jobs oecd reviews of vocational education and training. *Organisation for Economic Co-operation and Development (OECD).*

Hornstein, A., Krusell, P., & Violante, G. L. (2005). The effects of technical change on labor market inequalities. In *Handbook of economic growth*, volume 1 (pp. 1275–1370). Elsevier.

Huang, I., Guo, R., Xie, H., & Wu, Z. (2012). The convergence of information and communication technologies gains momentum. *The global information technology report*, 35–45.

Ince, H., Imamoglu, S. Z., Keskin, H., Akgun, A., & Efe, M. N. (2013). The impact of erp systems and supply chain management practices on firm performance: case of turkish companies. *Procedia-Social and Behavioral Sciences*, *99*, 1124–1133.

Kim, H. H. & Brynjolfsson, E. (2009). Ceo compensation and information technology. *ICIS 2009 Proceedings*, 38.

Kovács, G. L. & Paganelli, P. (2003). A planning and management infrastructure for large, complex, distributed projects: beyond ERP and SCM. *Computers in Industry*, *51*(2), 165–183.

Michaels, G., Natraj, A., & Van Reenen, J. (2014). Has ict polarized skill demand? Evidence from eleven countries over twenty-five years. *Review of Economics and Statistics*, *96*(1), 60–77.

Nicolaou, A. I. & Bhattacharya, S. (2006). Organizational performance effects of ERP systems usage: The impact of post-implementation changes. *International Journal of Accounting Information Systems*, *7*(1), 18–35.

Pantea, S., Sabadash, A., & Biagi, F. (2017). Are ICT displacing workers in the short run? Evidence from seven European countries. *Information Economics and Policy*, *39*, 36–44.

Payne, A. & Frow, P. (2006). Customer relationship management: from strategy to implementation. *Journal of Marketing Management*, *22*(1-2), 135–168.

Rosen, S. (1981). The economics of superstars. *The American economic review*, *71*(5), 845–858.

Ruivo, P., Mestre, A., Johansson, B., & Oliveira, T. (2014). Defining the ERP and CRM integrative value. *Procedia Technology*, *16*, 704–709.

Stockinger, B. (2019). Broadband internet availability and establishments' employment growth in germany: evidence from instrumental variables estimations. *Journal for Labour Market Research*, *53*(1), 7.

Stucki, T. & Wochner, D. (2018). Technological and organizational capital: Where complementarities exist. *Journal of Economics & Management Strategy*. forthcoming.

Wolter, S., Cattaneo, M., Denzler, S., Diem, A., Hof, S., Meier, M., & Oggenfuss, C. (2018). Swiss education report 2018. *SKBF/CSRE Swiss Coordination Centre for Research in Education, Retrieved from:* https://www.skbf-csre.ch/fileadmin/files/pdfs/bildungsberichte/2018/Swiss_Education_Report_2018.pdf.

Table A1: Summary statistics

	N	Mean	SD	Min	Max
Value added (in million)	6690	55.64	398.46	0.01	17589.33
Capital (in million)	6690	851.53	27371.01	0	1122100
Lower (no. of employees)	6690	57.54	260.32	0	9461.61
Trained (no. of employees)	6690	112.27	696.28	0	27130.52
Advanced (no. of employees)	6690	37.87	235.54	0	11738.70
Academic (no. of employees)	6690	21.45	135.48	0	5879.04
Use of ERP (0/1)	6690	0.55	0.50	0	1
Use of CRM (0/1)	6690	0.39	0.49	0	1
Use of SCM (0/1)	6690	0.15	0.35	0	1
Percentage of employees who regularly use the intranet (%)	6690	33.92	34.98	0	90
Percentage of employees who regularly use computers (%)	6690	51.28	31.05	0	90

Notes: Value added and capital stock are expressed in nominal terms.