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Reduction of ICT Investment Due to the 2008 Economic Crisis and ICT-Enabled Innovation Performance of Firms

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Abstract

In this paper, we examine empirically the possibility that an economic crisis could affect firms' innovation performance through the ICT investment channel. In connection with this, it is also interesting to analyze the ICT characteristics of a firm (both ICT inputs and ICT infrastructures) that are associated with its ICT-enabled innovation performance. Our study is based on firm data from the glass/ceramics/cement industry of six European countries. We find a statistically significant negative relationship between ICT-enabled product/service innovation and firm's crisis vulnerability with respect to ICT investment (pro-cyclical behavior) only for new products/services that contain ICT components. Employment of specialized ICT personnel, ICT infrastructure that supports firm's internal functions (use of a series of standard administration and production support ICT applications), e-procurement, ICT outsourcing (only for process innovation), the awareness of the relevance of new ICTs, and quality competition (only for product/service innovation) are ICT characteristics that positively correlate with ICT-enabled innovation. Our findings have interesting implications for research and practice.

Keywords Economic crisis · Information and communication technologies (ICT) · Innovation · ICT-enabled innovation

JEL Classification O31

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Introduction

The financial and economic crisis of 2008 affected negatively investment in general, and investment in ICT was not left unchanged (Rojko et al. 2010; Keeley and Love 2010; OECD 2009; ITU 2009). World ICT spending fell by around 4% in 2009 (OECD 2010). Nevertheless, the decrease of ICT investment has been lower than that of GDP worldwide, so that the ratio of ICT investment to GDP has increased. The 2009 decline of world spending in ICT is not as large in current US dollars as in 2001–02, owing to growth in non-OECD economies and the introduction of new products (OECD 2010). Worldwide, about 57% of the 2009 ICT spending was on communication services and hardware, 21% on computer services, 13% on computer hardware, and 9% on software; about 76% of world ICT spending is in the OECD countries (OECD 2010).

The theoretical expectation for the impact of crisis on ICT investment is qualitatively the same as for all other kinds of investment. The main idea is that independent of the source of financing the general investment propensity decreases in periods of economic recession. Firms are confronted with demand uncertainty that makes investment more risky than in "normal" or boom periods. Demand uncertainty forces firms to a pro-cyclical behavior. Empirical evidence supports mostly pro-cyclical behavior (for R&D investment see, e.g., Ouyang 2011; Guellec and Ioannidis 1999).

ICT use is according to previous literature an important driver of innovation activities and performance (Brynjolfsson and Saunders 2010; Kleis et al. 2012; Nambisan 2013; Lyytinen et al. 2016; Jha and Bose 2016). As a consequence, we expect that the drop of ICT investment during the crisis might cause a negative effect on specific ICT-enabled innovation performance. This would be the ICT-related effect of the 2008 crisis on innovation. Thus, the first research question we want to examine empirically refers to the possibility that an economic crisis could affect innovation performance through the ICT investment channel (i.e., by leading to lower ICT investment). In connection with this, it is also interesting to analyze firm's ICT characteristics (concerning ICT inputs and ICT infrastructures) that are associated with ICT-enabled innovation performance. This is the second research question we want to pursue in this paper. Given that ICT constitutes a growth-determining factor of increasing importance and that economic crises are an inevitable trait of market-based economies, it is of general interest to know the extent to which the ICT investment channel strengthens or weakens the negative implications of economic crisis on innovation performance.

In particular, in this study, we empirically investigate the effect of ICT investment reduction on six different types of ICT-enabled product/service and process innovation: (a) new products or services that contain ICT components; (b) new products or services for which ICT has played an important part in their R&D process; (c) new products and services for which ICT has played an important part in their market launch; (d) new processes that are supported by ICT; (e) new processes for which ICT has played an important part in their design; and (f) new processes for which ICT has played an important part in their implementation. Furthermore, we empirically investigate the effects on the above six types of ICT-enabled product/service and process innovation of three ICT inputs (two "internal" ones, ICT budget and ICT personnel, and also an "external" one, the use of ICT outsourcing services); of three different types of ICT infra-structures (both internal functions support and external environment transaction-oriented ones: use of standard ICT applications for supporting firm's internal administration and production functions, as well as use of e-sales and e-procurement for supporting firm's transactions with customers and suppliers); and finally of the awareness of the relevance of new ICTs.

Our study is based on firm data from the glass/ceramics/cement industry in six European countries. The glass, ceramics, and cement industry is an important supplier of the construction sector, and as a consequence, an industry that depends primarily on domestic demand. In this sense, the state of affairs in this industry reflects the situation of a country's part of the economy that is oriented to domestic demand.

We find a statistically significant negative relationship between ICT-enabled product innovation and crisis vulnerability, as measured by the extent of the reduction of ICT investment during the crisis (pro-cyclical behavior), but only for new products or services that contain ICT components and are therefore directly affected by crisis-related decreasing product demand. Otherwise, the reduction of ICT investment does not appear to impact significantly ICT-enabled innovation performance in the sectors that have been investigated in this study, even though it is shown that ICT inputs (such as specialized ICT personnel and ICT outsourcing) as well as internal support ICT infrastructure (standard ICT applications, such as ERP, SRM, CRM, and SCM) are important determinants of ICT-enabled innovation.

To our knowledge, there is no other study investigating these topics, so our paper has also the character of an explorative study in a new research field. We believe that our findings are interesting for both researchers and practitioners in the areas of ICT, firm management, and public policy-making.

The paper is structured as follows: "Conceptual Background, Related Literature, and Research Hypotheses" section presents the conceptual background, related literature, and the research hypotheses. "Data" section discusses the data. In "Model Specification" section, the specification of the models is presented, while in "Econometric Issues" section, econometric issues are discussed. In "Results" section, the results are presented and discussed. "Summary and Conclusions" section concludes the paper.

Conceptual Background, Related Literature, and Research Hypotheses

Crisis and ICT Investment

The theoretical expectation for the impact of economic crises on ICT investment is qualitatively the same as for all other kinds of investment. The main idea is that independent of the source of financing the general investment propensity decreases in periods of economic recession (Geroski and Gregg 1997). Firms are confronted with demand uncertainty that makes investment more risky than in "normal" or boom periods. Decreasing demand limits also internal financing of investment by past revenues. Uncertain economic perspectives reduce also the willingness of banks and other financial intermediaries to finance firms' investment projects. Of course, not all kinds of investment bear the same risk, with innovation projects being considered as quite risky, and buildings being seen as much less risky than other investment categories (see, e.g., Kahle and Stulz 2012; Gerner and Stegmaier 2013; Geroski and Gregg 1997). Further, not all types of firms bear the same risk, with small firms being confronted with more difficulties to finance investments in recession than large firms due to credit rationing by financial intermediates (for the theoretical background see, e.g., Stiglitz and Weiss (1981) for investment in general; Goodacre and Tonks (1995 for investment in innovation). Empirical evidence supports mostly pro-cyclical behavior (for R&D investment see, e.g., Ouyang 2011; Guellec and Ioannidis 1999).[1] So, in general, we expect that economic crisis would negatively affect ICT investment. This means that we expect that firms would behave *pro-cyclically* with respect to ICT investment.

However, there is an interesting paper examining also anti-cyclical behavior, which is worth mentioning: In a case study, Leidner et al. (2003) found based on interviews with 20 CIOs that firms reacted both pro- and anti-cyclically to the crisis of 2000–02 depending on their short-term or long-term time-horizon. Further, Bertschek et al. (2017) find in a study based on German firm data that during the crisis in 2008 and 2009, ICT-intensive firms were hit less hard than non-ICT intensive firms with respect to their productivity, presumably because they were more successful in introducing process innovations during this period. For a more comprehensive approach to economic crisis that takes into consideration the need of developing new structures in order to get out of the crisis, see Dubina et al. (2012).

ICT and Innovation

There are many ways through which the use of ICT can contribute to firms' innovation. According to Kleis et al. (2012), this can happen through three main channels. The first channel goes through the improvement of the management of the knowledge used in the innovation process. ICT enables an efficient storage and a high accessibility of this knowledge throughout an enterprise. Internal networks, e-mail systems, and electronic databases all facilitate the transfer of knowledge and the communication between innovation participants from different functions and geographic locations inside the firm. Second, ICT enables a more efficient cooperation in innovation with external partners. Information technology facilitates the exchange of information with external partners who are located far away from the focal firm. This is quite useful, as the creation of new knowledge through collaboration with other firms has become more and more important in the last 20 years (Enkel et al. 2009). Third, ICT contributes directly to the innovation production in several ways. Kleis et al. (2012) identified three main stages of the innovation process, for which the application of ICT has proved to be useful. First, the stage of the generation of ideas for new products can benefit from information systems (IS) (e.g., customer relationship management (CRM)) that enable a firm to collect and analyze extensively customers' communication and transaction data, and identify through them needs that can be covered by new products or significant modifications of existing products. Second, ICT enables the development of efficient design capabilities for new products. For example, technologies, such as computer-aided design (CAD) and computer-aided manufacturing (CAM), help to digitize a new product's design and make it available throughout the innovation process. Third, ICT helps integrate design and

[1] Due to the fact that empirical evidence is rather scarce for this approach, we refrain here from a discussion of the opposite theoretical approach of "opportunity cost" that postulates an anti-cyclical behavior (see, e.g., Rafferty and Funk 2004). For the supporting role of public ICT investment in reaction to the economic crisis in Germany, see Saam et al. (2016).

production systems, so that errors of information transfer and translation are reduced and, as a consequence, the efficiency of this last stage of the innovation process is increased (Tapscott et al. 2000; Brynjolfsson and Saunders 2010).

Nambisan (2013) in a review of relevant literature concludes that ICT can be of critical importance both for “innovation process” and “innovation outcomes.” On one hand, there is variety of ICT tools that can significantly support and increase the efficiency and the effectiveness of the whole innovation design and development process (such as collaboration support tools, data mining tools, decision support systems, social media, and virtual simulation tools). On the other hand, ICTs can provide critical components of innovative products (e.g., digital components can be added to products, offering new highly useful functionalities, increasing value for the customer), and also for the provision of new innovative services and the operation of new innovative processes.

Furthermore, beyond the above-mentioned IS research, similar conclusions have been derived by economic research, from a research stream on “intensive growth theory” (Elsadig 2006; Ahmed 2017): it has been concluded that ICT enables a more efficient and effective utilization of firm’s main inputs, capital and labor, leading to higher levels of output, by facilitating and supporting valuable innovations in firm’s processes, as well as products and services.

Considerable empirical research has been conducted in order to investigate empirically the potential of ICT to drive innovation, examining the effects of a firm’s ICT characteristics on its innovation activity, which is reviewed by Santoleri (2015) and Arvanitis et al. (2016). They are based on the estimation of “innovation models,” usually having as dependent variable a measure of firm’s innovation activity, and as independent variables, the main innovation promotion factors determined by relevant economic research (such as firm’s human resources, size, and competition), as well as firm’s ICT-related factors (concerning various types of firm’s “hard” and “soft” ICT capital; see Arvanitis et al. 2013).

Furthermore, it should also be mentioned that there has been more focused previous literature identifying the potential of specific ICT applications (both internal functions’ support and external environment transaction oriented ones) to drive innovation. Sedera et al. (2016) focus on the role of the enterprise systems (such as ERP, and CRM), which are increasingly used by firms for supporting their internal functions, as facilitator and support of innovation. They conclude that enterprise systems are powerful platforms that can drive and support process innovations (e.g., processes improvements, integration, and standardization). Also, they provide extensive data concerning all business functions (e.g., sales, production, procurement, financial management), which enable the identification of opportunities for innovations in firm’s internal processes as well as in products and services. Furthermore, they can support all the stages of the introduction of new innovative products (e.g., production, sale, and shipping). Kyriakou et al. (2016) conclude that both internal enterprise systems (ERP and CRM) and e-sales ones impact positively product/service as well as process innovation. So, in the present study, we leverage the conclusions of this more focused research, by investigating the effects of using the main types of these enterprise ICT applications on firm’s innovation activity.

In sum, there have been considerable empirical studies estimating “innovation models,” concerning the effects of various firm’s ICT characteristics (concerning ICT infrastructures, ICT applications, ICT personnel, etc.) on product/service as well as process innovation (Kleis et al. 2012; Arvanitis et al. 2013; Hall et al. 2013; Santoleri 2015; Sedera et al. 2016; Kyriakou et al. 2016; Cuevas-Vargas et al. 2016; Arvanitis et al. 2016; Kroh et al. 2018).

However, the models used in these studies concern "normal" economic periods and not periods of economic crisis, so they do not include crisis-related independent variables and do not examine the impact of various aspects of economic crisis on firms' innovation activity. Our study contributes to filling this research gap: it examines the impact of the reduction of ICT investment due to the economic crisis on firm's innovation activity. For this purpose, we estimate an "extended innovation model," which includes as independent variables important innovation promotion factors as defined by relevant economic research as well as firms' ICT inputs and infrastructure and also the reduction of ICT investment due to the economic crisis (see previous "Crisis and ICT Investment" section). Furthermore, our study focuses on ICT-enabled product and ICT-enabled process innovation. This way, our setting allows the investigation of the effects of firm's ICT investment reduction due to the crisis and at the same time, the impact of a variety of a firm's ICT characteristics on a highly important kind of innovation: the ICT-based innovation.

As a result of the above discussion of empirical literature, we expect a positive impact of ICT characteristics on innovation performance, through the three channels identified by Kleis et al. (2012); this positive impact is expected to refer to both the innovation process and the innovation outcomes (Nambisan 2013). Also, we expect a negative impact of ICT investment reduction on innovation.

Research Hypotheses

Based on the above discussion of literature, we formulate the main idea of this paper as follows: Given that firms behave pro-cyclically with respect to ICT investment, i.e., reduce ICT investment under the negative influence of the economic crisis, and given that ICT investment impacts positively innovation performance in general, it can be expected that the economic crisis could affect negatively a firm's innovation performance *through the reduction of ICT investment as a channel*. Thus:

Hypothesis 1 *ICT-enabled* innovation performance measures are *negatively* correlated with the extent of a firm's crisis vulnerability with respect to ICT-related investment (as measured by the extent of reduction of ICT investment during the crisis).

Our second and third hypotheses aim at a concretization of the positive relationship between a firm's ICT-related inputs and ICT infrastructures and innovation performance:

Hypothesis 2 The ICT characteristics that refer to ICT inputs (ICT budget, ICT human capital, ICT outsourcing) are *jointly positively* associated with *ICT-enabled* innovation performance measures.

Hypothesis 3 The ICT characteristics that refer to ICT infrastructure (as represented by the ICT applications used by a firm) are *jointly positively* associated with *ICT-enabled* innovation performance measures.

Data

The data used in this study have been collected in the e-Business Survey 2009 conducted by the European Union. The survey focused on companies from the glass, ceramics, and cement industries of six EU countries: Germany, Spain, France, Italy, UK, and Poland, and consisted of 676 telephone interviews with ICT decision-makers, using computer-aided telephone interview (CATI) technology.

The questionnaire contained about 90 questions, which were structured into nine modules (background information, use of ICT systems, e-commerce and automated data exchange, e-sales, automated data exchange, innovation activity, ICT skills requirements, ICT investment and future trends, ICT energy efficiency, and emissions). The survey population was defined as companies with at least 10 employees, which used computers, were active within the national territory of one of the above-mentioned six countries covered and which had their primary business activity in the glass, ceramics, or cement industry as specified by NACE Rev. 2 Groups 23.1-6. The survey was carried out as an enterprise survey: data collection and reporting focus on the enterprise, defined as a business organization (legal unit) with one or more establishments. The sample drawn was a stratified random sample of companies from the population in each of the six countries, with the objective of fulfilling minimum strata with respect to company size-bands per country-sector cell (see “Annex I: Methodology Report” in Sectoral e-Business Watch 2009). Pilot interviews prior to the regular fieldwork were conducted with about 15 companies in Germany in February 2009, in order to test the questionnaire (structure, comprehensibility of questions, average interview length). The response rate, i.e., the number of completed interviews divided by the net sample of contacts established with eligible hospitals/enterprises, was typically about 15–20%, with, however, big differences in some of the countries.

Two subsets of the initial dataset were used for our econometric estimates: the first one contained 247 observations corresponding to firms having reported product/service innovations in the past 12 months (product/service innovators subset); and the second one contained 291 observations corresponding to firms having reported process innovations in the past 12 months (process innovations subset). In this survey if a firm reported that it has introduced product/service (process) innovations in the past 12 months, this firm was further asked in the questionnaire, whether it has introduced three specific categories of ICT-enabled product (process) innovations. Table 4 in the Appendix shows the composition of these two datasets used for the econometric estimates by country and sub-sector (second and third columns).

Model Specification

Dependent Variables

We exploit the available information in the above-mentioned survey concerning the introduction of product/service and process innovations in the 12-month period before the survey in 2009 that are closely related to ICT and distinguish six different measures/types of ICT-enabled product and process innovation concerning: (a) new products or services that contain *ICT components*; (b) new products or services for which ICT has played an important part in their *R&D process*; (c) new products and services for which ICT has played an important part in their *market launch*; (d) new processes that are supported by

ICT; (e) new processes for which ICT has played an important part in their *design*; and (f) new processes for which ICT has played an important part in their *implementation*. We construct six three-level ordinal variables INNOPD_ICT1, INNOPD_ICT2, INNOPD_ICT3, INNOPC_ICT1, INNOPC_ICT2, and INNOPC_ICT3 (see Table 5 in the Appendix for the definition of these variables). These variables allow a differentiated measurement of the specific contribution of ICT to product and process innovation.

Independent Variables

ICT Investment Crisis Vulnerability

We construct a binary variable (ICT_CRISIS) based on the following question of the e-Business Survey 2009: "Has the economic crisis an impact on your ICT investment plans or on ICT projects?" (see Table 5 in the Appendix). The variable is codified as follows: 0: no impact; 1: "yes, but *no* ICT or e-business projects were cancelled or significantly downsized," or "yes, ICT or e-business projects were cancelled or significantly downsized."[2] We expect a *negative* correlation of this ICT investment crisis vulnerability variable with all six measures for *ICT-enabled* innovation (Hypothesis 1). In order to avoid distortions due to the endogenous character of the crisis variable, this variable has been itself regressed on a series of explaining variables (see Table 8 in the Appendix and the discussion in "Econometric Issues" section below).

Further, we distinguish three other groups of independent variables (see Table 5 in the Appendix for more details).

ICT Inputs

We use three variables, one related to the availability of ICT-specific human resources (ICT_personnel; a binary variable), one concerning the available financial resources (ICT_ budget; a three-level ordinal variable), and one referring to an external ICT input, the existence of ICT-outsourcing as means for reducing ICT-related costs.

ICT Infrastructure

In the survey, information is available for the use of a wide spectrum of standard ICT applications aiming at the support of firm's internal functions, such as "enterprise resource planning" (ERP), "supply chain management" (SCM), "supplier relationship management" (SRM), and CRM. Further applications ("computer-aided design" CAD, "computer aided manufacturing" CAM) refer to manufacturing activities in the more narrow sense. We construct a composite variable for firms that use at least one of these technologies (ICT_INFRA). A further composite variable is constructed for firms for which one or more of the following novel technologies are of relevance (in the sense that firms are aware of and have interest in them): service-oriented architectures, web 2.0 applications, data warehousing and data mining, and mobile services, such as mobile commerce and remote access technologies (ICT_NEWTECH).

[2] We constructed also a three-level ordinal variable that showed similar results as the binary one. We prefer to show here the estimates for the simpler binary variable.

We also included two independent variables concerning the use of two ICT applications aiming to support transaction with firm's external environment (e-commerce), e-procurement, and e-sales, respectively. The e-commerce is an important ICT application that serves to manage the firm external functions as consumer (e-procurement variable E_P) as well as supplier of goods and services (e-sales variable E_S). Both e-commerce variables are six-level ordinal variables (see Table 5 in the Appendix).

According to Hypotheses 2 and 3, we expect a *joint positive* effect of these two groups of variables representing ICT inputs and ICT infrastructure, respectively, but we do not dispose of more detailed hypotheses regarding the effects of each single variable in the above-mentioned groups of ICT variables.

Market Conditions

We distinguish three dimensions of competition at the product market: price competition (PCOMP), quality competition (QCOMP), and customer service competition (SCOMP). The respective measures of the importance of these types of competition for the firms are three-level ordinal variables. We expect a *joint positive* effect for these three competition variables according to standard economic theory and empirical evidence (see, e.g., Cohen 2010 for a comprehensive survey of studies on innovation economics at the firm level).

Other Firm Characteristics

Controls are inserted in the estimation equation for firm size, sub-sector, country, strong export-orientation (EXPORT), and also the firm being part of a multinational corporation (INTER). The economic crisis that started in 2008 has led to a decrease of world trade volume, thus of exports. Export-oriented firms have been stronger exposed to this particular crisis component than firms that primarily cover the domestic demand. Thus, we expect that export-oriented firms of the glass, ceramics, and cement sector, which is primarily oriented to domestic demand, would be particularly affected by the crisis. Finally, we expect a positive effect for firm size according to standard economic theory and empirical evidence (see, e.g., Cohen 2010).

Formally expressed our innovation equations are as follows:

$$\begin{aligned}[\mathrm{INNOPD\_ICTx};\ \mathrm{INNOPC\_ICTx}]_i = {} & a_0 + a_1\ \mathrm{ICT\_CRISIS} + a_2\ \mathrm{ICT\_budget}_i \\ & + a_3\ \mathrm{ICT\_outsourcing}_i + a_4\ \mathrm{ICT\_personnel}_i \\ & + a_5\ \mathrm{ICT\_INFRA}_i + a_6\ \mathrm{ICT\_NEWTECH} \\ & + a_5\ \mathrm{E\_P}_i + a_6\ \mathrm{E\_S}_i + a_7\ \mathrm{PCOMP} \\ & + a_8\ \mathrm{QCOMP} + a_9\ \mathrm{SCOMP}_i + a_{10}\ \mathrm{INTER}_i \\ & + a_{11}\ \mathrm{EXPORT}_i + a_{12}\ \mathrm{medium{-}sized}_i \\ & + a_{13}\ \mathrm{large}_i + \mathrm{sector\ controls} \\ & + \mathrm{country\ controls} + e_i \qquad (1)\end{aligned}$$

where *x*: 1, 2, 3; (for firm *i*)

Table 6 in the Appendix contains descriptive statistics for all the above dependent and independent variables of our study for the observations used in our empirical work. Table 7 in the Appendix shows the correlations between the model variables. Also, in the fourth and fifth columns of Table 4 of the Appendix, we can see for the ICT Investment Crisis Vulnerability variable (ICT_CRISIS), the percentage of firms in which the economic crisis had a negative impact on ICT investment by country and sub-sector. We remark that this percentage is similar among the three examined sub-sectors, being a little lower in the cement industry (the chi^2 independence test has shown independence between ICT_CRISIS and sector). However, it varies substantially among the six examined countries, having higher values for Spain, Poland, and Italy and lower ones for Germany, France, and UK (the chi^2 independence test has shown dependence between ICT_CRISIS and country); this is in agreement with our expectations, as we know that the negative effect of the economic crisis was stronger in the Southern Europe than in the Northern Europe.

Econometric Issues

Ordered Probit

Due to the ordinal character of the six three-level dependent variables, the appropriate econometric method would be an ordered probit regression. For the estimation of the respective models, we applied the STATA-procedure "oprobit."

Endogeneity Problem

Due to the cross-section character of our data, both the left-hand and the right-hand variables refer to the same time period. As a consequence, our estimates of the six ICT-enabled innovation equations have to be seen primarily as an extensive analysis of conditional correlations between the independent variables (that are considered as structural characteristics that change only slowly over time) and the ICT-enabled innovation indicators. Nevertheless, some robust regularities come out, which if interpreted in view of our hypotheses presented in "Conceptual Background, Related Literature, and Research Hypotheses" section could possibly indicate the direction of causal links.

However, the possible distorting effect of the ICT investment crisis vulnerability variable, which is considered to be an endogenous one, in the innovation equations summarized in Eq. (1) has to be taken into account. To this end, we applied the procedure developed by Rivers and Vuong (1988) to test the exogeneity of the crisis variable in the innovation equations. In a first step, we estimated an equation explaining ICT_CRISIS, which contained the same variable as in Eq. (1) and in addition, the variable *ICT_skill_deficits* (see Table 8 in the Appendix).[3] We calculated the residual (predicted value minus effective value of variable ICT_CRISIS) in Eq. (1) and inserted it as a further right-hand variable in the innovation equations summarized in Eq. (1). Bootstrapping was used in order to correct

[3] For the binary variable ICT_CRISIS, we used a maximum likelihood probit model (STATA-procedure "probit").

the standard errors of the estimated parameters. As instrument, we used the variable *ICT_skill_deficits*, which is significantly correlated with ICT_CRISIS, but not with any of the ICT-enabled innovation variables, and is not included in the specification of Eq. (1). The idea behind this instrument is that lack of ICT skills could—at least partially—be a problem due to limited supply of ICT-skilled personnel in some countries, thus exogenous to firms. The coefficients of the residual variables were not statistically significant at the 10% test level in any of the innovation equations. As a consequence, the estimates in Tables 3 and 4 are based on the original ICT investment crisis vulnerability variable. The detailed results of the exogeneity tests are available upon request.

Other Issues

Multicollinearity is not an issue in our estimations as shown in the correlation matrix in Table 7 in the Appendix. Marginal effects were not estimated because 14 out of 21 right-hand variables in Eq. (1) are dummy variables and the rest 7 are (three-level and six-level) ordinal variables.

Results

ICT-Enabled Product Innovation

The relationship between ICT-enabled product innovation and ICT investment crisis vulnerability is negative for all three examined categories of ICT-enabled product innovation, but only for INNOPD_ICT1 (new products containing ICT components) is this relationship statistically significant (column 1 in Table 1). The explanation for this negative effect is straightforward: the stronger the crisis impact on ICT investment, the less ICT-enabled innovation can be generated, particularly in the case of products and services that directly contain ICT components. This finding is in accordance with Hypothesis 1. However, the statistically significant negative relationship is found only for new products or services that contain ICT components and are therefore *directly* affected by decreasing product demand. No significant relationship could be found for the *indirect* influence of ICT on product innovation through the R&D or marketing channel (see the definition of the three types of ICT-enabled product innovation in Table 5 in the Appendix). Thus, Hypothesis 1 receives only partly empirical support.

The *joint* effect of all variables for ICT inputs is positive and statistically significant for INNOPD_ICT1 and INNOPD_ICT2, but not for INNOPD_ICT3 (Table 9 in the Appendix). So, Hypothesis 2 is confirmed only for the first two categories of ICT-enabled product innovation. This is not the case for the third category, indicating that ICT inputs have not been important for the market launch of new product or services. The *joint* effect for the variables for ICT infrastructure is positive and statistically significant for all three categories of ICT-enabled product innovation (Table 9 in the Appendix). So, Hypothesis 3 is fully confirmed.

ICT budget change due to the crisis is not relevant for all three types of ICT-enabled product innovation, presumably because the main effect of reduced financing of ICT is captured by the ICT investment crisis vulnerability variable. Also, ICT-outsourcing does not correlate significantly with the product innovation variables, probably because

Table 1 Ordered probit estimates for INNOPD_ICT1, INNOPD_ICT2, and INNOPD_ICT3

	INNOPD_ICT1	INNOPD_ICT2	INNOPD_ICT3
ICT_CRISIS	− 0.394**	− 0.051	− 0.051
	(0.197)	(0.182)	(0.167)
ICT inputs			
ICT_budget	0.032	0.024	− 0.097
	(0.157)	(0.148)	(0.154)
ICT_outsourcing	0.270	0.018	− 0.018
	(0.172)	(0.188)	(0.174)
ICT_personnel	0.548***	0.506***	0.446**
	(0.198)	(0.188)	(0.185)
ICT infrastructure			
ICT_INFRA	1.013***	0.305	0.281
	(0.375)	(0.375)	(0.382)
ICT_NEWTECH	0.548*	0.584**	0.433***
	(0.310)	(0.284)	(0.223)
E_P	0.190***	0.192***	0.092
	(0.072)	(0.074)	(0.069)
E_S	0.042	0.087	0.054
	(0.079)	(0.079)	(0.073)
Market conditions			
PCOMP	0.183	0.150	0.213
	(0.162)	(0.146)	(0.135)
QCOMP	0.015	0.547**	0.288
	(0.234)	(0.232)	(0.187)
SCOMP	0.213	− 0.077	− 0.057
	(0.149)	(0.141)	(0.228)
Other firm characteristics			
INTER	− 0.130	0.116	− 0.055
	(0.225)	(0.210)	(0.228)
EXPORT	− 0.386*	− 0.186	− 0.146
	(0.216)	(0.211)	(0.183)
Medium-sized	0.214	0.339*	0.105
	(0.215)	(0.206)	(0.191)
Large	0.174	0.498*	− 0.260
	(0.306)	(0.275)	(0.248)
Sector dummies (2)	Yes	Yes	Yes
Country dummies (5)	Yes	Yes	Yes
Const. (2)	Yes	Yes	Yes
N	247	247	247
Pseudo R^2	0.195	0.174	0.090
Wald chi^2	88.4	60.2	42.4
Prob > chi^2	0.000	0.000	0.006
Log pseudo-likelihood	− 173.9	− 187.7	− 210.0

Note: Heteroskedasticity-robust standard errors in brackets; ***. **, and * denote statistical significance at the 1, 5, and 10% test levels, respectively; reference for "medium-sized," "large": "small" the ICT required for these three categories of ICT-enabled innovation is highly specialized and firm-specific, so it cannot be provided through outsourcing.

Having specialized ICT personnel is significantly positively correlated with all three categories of ICT-enabled product innovation; this indicates the important role of ICT personnel for the exploitation of ICT for product innovations. Also, for all these three types of innovation, the degree of perceived relevance of novel ICT technologies (ICT_NEWTECH) is positively correlated with innovation; this indicates that firms generating ICT-enabled product innovations have higher awareness of and show higher interest in novel ICT, in order to exploit them for further product innovations. Standard ICT applications supporting firm's internal functions (ICT_INFRA) seem to be of relevance only for the first category of ICT-enabled product innovation (ICT components in products), but not for the other two (ICT in R&D processes; ICT in the market launching of new products). Only one component of e-commerce, e-procurement, appears to be important for the first two innovation categories, but not for the third one.

The *joint* effect of competition conditions is positive and statistically significant for INNOPD_ICT2 and INNOPD_ICT3 (Table 9 in the Appendix). This finding is in accordance with our theoretical expectation. Price competition and customer service competition are not relevant for ICT-enabled product innovation. Only one competition component, quality competition, is positively correlated with INNOPD_ICT2; this indicates that quality competition is a driver for the use of ICT in the R&D processes for improving their efficiency and effectiveness.

Belonging to a group of firms (national or international conglomerate) is not important for ICT-enabled product innovation. Being active at international markets correlates negatively only with INNOPD_ICT1, but shows no effect on the other two innovation categories.

A further interesting result refers to the absence of a size effect in the estimates of INNOPD_ICT1 and INNOPD_ICT3. The likelihood of ICT-enabled product innovation by adding ICT components in new products or using ICT for the market launching of them in the glass/ceramics/cement industry appears to be independent of firm size, and innovation activities are not concentrated in large firms, as it is often the case in other industries. This is not the case for INNOPD_ICT2: in these estimates, we find a positive effect for medium-sized firms and large firms (as compared to small firms) with respect to the use of ICT in the R&D processes.

ICT-Enabled Process Innovation

The relationship between ICT-enabled process innovation and ICT investment crisis vulnerability is not statistically significant for all three examined categories of ICT enablement in process innovation (Table 2). The decrease of ICT investment due to the crisis is not correlated with the introduction of ICT-enabled process innovation. This is not in accordance with Hypothesis 1. Presumably, firms continued improving their internal processes in the crisis period using the existing ICT resources in innovative ways and more efficiently than before.

The *joint* effect of the variables for ICT inputs as well as for the variables for ICT infrastructure is positive and statistically significant for all three ICT-enabled process innovation variables (Table 9 in the Appendix). *Hypotheses* 2 and 3 are thus confirmed for all three categories of ICT-enabled process innovation.

Table 2 Ordered probit estimates for INNOPC_ICT1, INNOPC_ICT2, and INNOPC_ICT3

	INNOPC_ICT1	INNOPC_ICT2	INNOPC_ICT3
ICT_CRISIS	− 0.154	− 0.183	− 0.123
	(0.155)	(0.158)	(0.159)
ICT inputs			
ICT_budget	− 0.111	− 0.176	− 0.082
	(0.133)	(0.128)	(0.133)
ICT_outsourcing	0.223	0.362**	0.497***
	(0.158)	(0.158)	(0.158)
ICT_personnel	0.333**	0.508***	0.407***
	(0.163)	(0.160)	(0.161)
ICT infrastructure			
ICT_INFRA	1.144***	0.282	0.932***
	(0.355)	(0.338)	(0.349)
ICT_NEWTECH	0.737***	0.851**	0.911***
	(0.207)	(0.233)	(0.242)
E_P	0.109	0.165**	0.092
	(0.069)	(0.073)	(0.069)
E_S	0.082	0.057	0.054
	(0.067)	(0.068)	(0.073)
Market conditions			
PCOMP	0.001	− 0.018	0.213
	(0.120)	(0.125)	(0.135)
QCOMP	− 0.025	0.039	0.288
	(0.185)	(0.211)	(0.187)
SCOMP	− 0.100	− 0.176	− 0.057
	(0.119)	(0.122)	(0.228)
Other firm characteristics			
INTER	0.389**	0.595***	− 0.055
	(0.197)	(0.208)	(0.228)
EXPORT	− 0.172	− 0.247	− 0.146
	(0.192)	(0.206)	(0.183)
Medium-sized	0.628***	0.603***	0.105
	(0.178)	(0.180)	(0.191)
Large	0.494**	0.708***	− 0.260
	(0.234)	(0.222)	(0.248)
Sector dummies (2)	Yes	Yes	Yes
Country dummies (5)	Yes	Yes	Yes
Const. (2)	Yes	Yes	Yes
N	291	291	291
Pseudo R^2	0.196	0.208	0.199
Wald chi^2	123.1	107.9	115.7
Prob > chi^2	0.000	0.000	0.000
Log pseudo-likelihood	− 253.2	− 239.6	− 241.1

Note: Heteroskedasticity-robust standard errors in brackets; ***. **, and * denote statistical significance at the 1, 5, and 10% test levels, respectively; reference for “medium-sized,” “large”: “small”

There is a common pattern for all three examined categories of ICT-enabled process innovation: availability of ICT-specialized personnel and ICT outsourcing (with the exception of INNOPC_ICT1) plays an important role for all three of them. Presumably, the ICT needed for process innovation is less firm-specific than for product innovation, so that outsourcing becomes a valid alternative to the development of firm-specific ICT-applications inside the firm. The perceived interest in novel technologies is also positively associated with ICT-enabled process innovation; this indicates that firms introducing ICT-enabled process innovations have higher awareness of and show higher interest in novel ICT, in order to exploit them for further process innovations. E-procurement is relevant only for INNPC_ICT2.

Competition does not seem to be of any relevance for all three types of ICT-enabled process innovation, which is not what we would theoretically expect especially with respect to price competition. *Joint* effects are statistically insignificant for all three process innovation categories (Table 9 in the Appendix). So, competition is not a driver of ICT-enabled process innovations in these three manufacturing sectors.

Belonging to a group of firms is important for the first two categories of ICT-enabled process innovation. Presumably, such firms have better access to ICT, as well as ideas/ways of exploiting them for making process innovations, from other member firms of the same conglomerate. Being active at international markets does not correlate with ICT-enabled process innovation.

In the estimates for the variables INNOPC_ICT1 and INNOPC_ICT2, larger firms and medium-sized firms show a significantly stronger tendency to ICT-enabled process innovation than small firms. Thus, for ICT-enabled process innovation a size effect is found; bigger firm size leads to more complex processes, with numerous steps and involved employees, so there is stronger motivation for and benefit from exploiting the capabilities offered by ICT in order to generate process innovations.

Additional Estimates for Overall Innovation

In a last step, we also estimated our model for overall product/service innovation and overall process innovation, in order to highlight differences and similarities of the influence of our model variables on overall innovation in comparison with ICT-related innovation. The respective probit estimates for the binary dependent variables INNOPD and INNOPC (introduction of product/service and process innovations, respectively, in the 12 months period before the survey) are shown in Table 3.[4] The variable ICT_CRISIS is not significant in both estimates, contrary to the finding of a negative and significant coefficient of this variable in the estimates for ICT-related product innovation (INNOPD_ICT1) in Table 2. This means that the reduction of ICT investment due to the crisis does not appear to have an influence on overall innovation. Thus, ICT investment reduction is not a channel through which the 2008 economic crisis could have impacted overall innovation performance in the economy sector that has been investigated in this study.

We find similar positive effects of the ICT endowment variable ICT_INFRA and the variable for the perceived relevance of new technologies ICT_NEWTECH for all categories of innovation in Tables 1, 2, and 3. This is an important result that

[4] For these estimates we could use all 676 available observations.

Table 3 Probit estimates for INNOPD and INNOPC (introduction of product/service and process innovations, respectively, in the 12-month period before the survey)

	INNOPD	INNOPC
ICT_CRISIS	0.183	0.166
	(0.118)	(0.117)
ICT inputs		
ICT_budget	0.303***	0.083
	(0.113)	(0.116)
ICT_outsourcing	0.462***	0.217
	(0.147)	(0.145)
ICT_personnel	− 0.010	0.389***
	(0.135)	(0.135)
ICT infrastructure		
ICT_INFRA	0.468***	0.700***
	(0.259)	(0.270)
ICT_NEWTECH	0.142***	0.149***
	(0.038)	(0.040)
E_P	0.048	0.105**
	(0.050)	(0.052)
E_S	0.064	− 0.012
	(0.055)	(0.055)
Market conditions		
PCOMP	− 0.027	− 0.009
	(0.097)	(0.097)
QCOMP	0.046	0.052
	(0.121)	(0.127)
SCOMP	0.093	0.040
	(0.088)	(0.087)
Other firm characteristics		
INTER	− 0.081	− 0.072
	(0.177)	(0.175)
EXPORT	0.038	0.127
	(0.146)	(0.144)
Medium-sized	0.070	0.120
	(0.123)	(0.123)
Large	0.125	0.019
	(0.198)	(0.195)
Sector dummies (2)	Yes	Yes
Country dummies (5)	Yes	Yes
Const.	Yes	Yes
N	676	676
Pseudo R^2	0.121	0.168
Wald chi^2	98.9	137.7
Prob > chi^2	0.000	0.000
Log pseudo-likelihood	− 390.1	− 384.4

Note: Heteroskedasticity-robust standard errors in brackets; ***. **, and * denote statistical significance at the 1, 5, and 10% test levels, respectively; reference for “medium-sized,” “large”: “small” demonstrates the relevance of ICT use for innovation at firm level. A further interesting finding refers to the role of ICT personnel that seems to be only for overall process innovation of relevance, contrary to all six categories of ICT-related innovation that positively correlate with the existence of specialized ICT-personnel. Further, there are differences of minor importance as to e-procurement, ICT budget, and ICT outsourcing.

Summary and Conclusions

Crisis and Innovation Performance

Given that ICT constitutes a growth-determining factor of increasing importance and that economic crises are an inevitable trait of market-based economies, it is of general interest to know the extent to which the ICT investment channel strengthens or weakens the negative implications of economic crisis on innovation performance.

A statistically significant negative relationship between ICT-enabled innovation and ICT investment crisis vulnerability has been found only for new products or services that contain ICT components and is therefore *directly* affected by the crisis-induced decrease of ICT-related investment. Only for this type of ICT-related innovation appears pro-cyclical behavior to be dominant. No significant relationship could be found for the *indirect* influence of ICT on product innovation through the R&D or marketing channel. Furthermore, the decrease of ICT investment is not correlated with the introduction of ICT-enabled process innovation. This is not in accordance with Hypothesis 1. Presumably, firms continued to improve their production processes in the crisis period using their existing ICT resources in innovative ways and more efficiently than before; also, they leverage existing ICT resources for supporting their R&D processes as well as for market launching of new products. On the whole, Hypothesis 1 receives only partly empirical support. The economic crisis 2008 affected innovation performance only partly through the ICT investment channel for the sectors that have been investigated in this study. Though according to relevant IS research (Kleis et al. 2012; Nambisan 2013) as well as economics research ("intensive growth theory"; see Elsadig 2006; Ahmed 2017) ICT is of critical importance for firm's processes, products, and services innovation, which enables a more efficient and effective utilization of firm's capital and labor and leads to higher levels of output, this specific reduction in ICT investment caused by the recent economic crisis does not seem to affect negatively firms' innovation activity in these sectors; probably, firms in this crisis period did not cut innovation-critical ICT investment, and at the same time, they exploited better their existing ICT inputs and infrastructures.

ICT Characteristics and Innovation Performance

ICT inputs and ICT infrastructure seem to be relevant for innovation performance. For five out of six ICT-enabled categories of product and process innovation that are taken into consideration in this study, we find a statistically significant positive *joint* effect of the variables for ICT inputs and ICT infrastructure on innovation performance. Hypotheses 2 and 3 receive support from our findings. The "internal" ICT infrastructures that support firm's internal administrative and production functions (ERP, CRM, SCM, SRM, CAD, CAM) seem to have a stronger impact on ICT-enabled innovation than the "external transaction" (e-commerce) ICT infrastructures (as the use of e-sales is not relevant for all six examined innovation categories, while the use of e-procurement is relevant for only three of them).

Human resources in form of ICT-specialized personnel are important for all six categories of ICT-enabled innovation. For two out of six examined innovation categories, the ICT outsourcing, reflecting a strategy of efficiency increase of the use of ICT resources, is also relevant; outsourcing constitutes an efficient and effective way of obtaining the ICT required for the design and implementation of process innovations. A common innovation-relevant characteristic for all six examined ICT-enabled innovation categories is the awareness of and interest in novel technologies, such as service-oriented architectures, web 2.0 applications, data warehouse and data mining, and mobile services, such as mobile commerce and remote access technologies. Monitoring and assessing the continuously emerging new ICT lead to the identification of opportunities of exploiting them for product/ service and process innovation.

Implications for Research and Practice—Future Research

Our study has interesting implications for research and practice. With respect to the former, it enriches our knowledge on the consequences of economic crises, improving our understanding concerning their impact on innovation through the ICT investment channel. Also, it enriches our knowledge concerning the effects of different ICT inputs (both internal and external ones) as well as different types of ICT infrastructures (both internal functions support and external environment transaction oriented ones) on innovation. It adds to the existing knowledge concerning the use of ICT outsourcing beyond ICT cost reduction, for supporting innovation (which has been an important research topic in IS research, see, e.g., Oshri et al. 2015), identifying some areas where this is feasible, and some other areas where this does not happen.

With respect to practice, our findings indicate that despite the reduction of ICT investment that occurs in many firms during economic crises, this does not have necessarily to lead to reduced ICT-based innovation, as firms can leverage for this purpose their existing ICT resources by using them more efficiently and innovatively. Only for some categories of advanced ICT-enabled innovations, some additional ICT investments seem to be necessary. Such innovations concern the development of new products equipped with ICT components, which are increasingly pursued by firms, taking advantage of the development of the "Internet of Things" (IoT), see, e.g., Li et al. (2015). Without these additional ICT investments, progress towards new generations of innovative ICT-enabled products following the IoT trends will slow down. Furthermore, our findings indicate that firms' internal ICT infrastructures (supporting their internal administrative and production functions), ICT personnel, as well as the continuous monitoring and assessment of the continuously emerging new ICT are important for their innovation performance, so it is important to place much emphasis on them.

The main limitation of our study is that it has been based on data from the glass, ceramics, and cement manufacturing industries of six European countries, so our findings may have been influenced to some extent from this particular sectoral and national context. So, further research is required in order to investigate the main research questions dealt with in this study in different sectoral and national contexts. Furthermore, our study has been based on data from year 2009, so it would be interesting to repeat the analysis for another year, or set of years, and check if the 2009 results are consistent with what happened in other years. Another limitation is that we have examined the effects on ICT-enabled innovation (and innovation in general) of the reduction of ICT investment in general (without discriminating between reductions in different types of ICT investment) and also of a limited number of ICT inputs and infrastructures. So, further research is required in order to investigate the effects on ICT-enabled innovation (and innovation in general) of reductions in different types of ICT investment (corresponding to different types of ICT use), as well as of a wider range of firm's ICT "resources and capabilities" identified in previous relevant literature (e.g., Gu and Jung 2013). Finally, this study can be extended by investigating (a) the effects of our main variables (both ICT and innovation related ones) on firm's productivity and (b) the effects of crisis induced reductions in other types of firms' investments (e.g., in production equipment) on their innovation activity and productivity.

Appendix

Table 4 European glass, ceramics and cement industry: composition of the product/service innovators' and process innovators datasets by country and sub-sector (columns 2 and 3); percentage of firms having reductions of ICT investment due to the economic crisis per country and sub-sector (columns 4 and 5) among product/service innovators' and process innovators

Country	Product/service innovators (*N* = 247) %	Process innovators (*N* = 291) %	ICT invest. reduction product/service Innovators (*N* = 247) %	ICT invest. reduction process Innovators (*N* = 291) %
Germany	26.3	24.4	30.8	32.4
Spain	18.2	18.9	55.6	69.1
France	7.3	7.2	50.0	47.6
Italy	16.2	13.4	60.0	53.8
UK	8.9	8.9	54.5	46.2
Poland	23.1	27.2	68.4	64.6
Total	100	100		
Sub-sector	%	%	%	%
Glass	24.7	26.1	57.4	50.0
Ceramics	29.1	23.7	54.2	58.0
Cement	46.2	50.2	48.4	52.7
Total	100	100		

Table 5 Definition of variables

Variables	Definition
Dependent variables	
INNOPD_ICT1	The new products or services have ICT components; binary variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPD_ICT2	ICT has played an important part in the R&D process which led to the new products or services; ordinal variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPD_ICT3	ICT has played an important part in the market launch of the new products or services; ordinal variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPC_ICT1	The new processes are supported by ICT; ordinal variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPC_ICT2	ICT has played an important part in the process design; ordinal variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPC_ICT3	ICT has played an important part in the implementation of the new processes; ordinal variable: 0: no; 1: yes, partly; 2:yes, fully
INNOPD	Introduction of product innovations in the period 2007–2009
INNOPC	Introduction of process innovations in the period 2007–2009
Independent variables	
ICT_CRISIS	Impact of the economic crisis on ICT investment plans or on ICT projects; binary variable: 1: yes, but no ICT or e-business projects were canceled or significantly downsized or yes, ICT or e-business projects were canceled or significantly downsized; 0: no impact
ICT_budget	Change of ICT budget (covering primarily current variable costs and depreciation): three-level ordinal variable: 0: decrease; 1: no change; 2: increase
ICT_personnel	Employment of ICT practitioners; binary variable: 1: yes; 0: no
ICT_skill deficits	Have the employees problems because of insufficient computer skills? Binary variable: 1: yes; 0: no
ICT_NEWTECH	Relevance for the company of: service-oriented architectures; web 2.0 applications; data warehousing and data mining; mobile services such as mobile commerce and remote access technologies; binary variable; 1: yes; 0: no
ICT_INFRA	Average of the binary variables for the use (or not) of “enterprise resource planning” (ERP); “supply chain management” (SCM); “supplier relationship management” (SRM); “customer relationship management” (CRM); “computer-aided design” (CAD); “computer-aided manufacturing” (CAM)
E_P	Use of e-procurement: 6-level ordinal variable: 0: no e-procurement; 1: less than 5% of purchases; 2: 5–10%; 3: 11–25%; 4: 26–50%; 5: 50% and more
E_S	Use of e-sales: 6-level ordinal variable: 0: no e-sales; 1: less than 5% of sales; 2: 5–10%; 3: 11–25%; 4: 26–50%; 5: 50%; and more
PCOMP	Importance of price competition in the main market; three-level ordinal variable: 0: not important; 1: quite important; 2: very important
QCOMP	Importance of quality competition in the main market; three-level ordinal variable: 0: not important; 1: quite important; 2: very important
SCOMP	Importance of customer service competition in the main market; three-level ordinal variable: 0: not important; 1: quite important; 2: very important
INTER	Part of a multinational enterprise; binary variable: 1: yes; 0: no
EXPORT	International market as most important sales market; binary variable: 1: yes; 0: no
Medium-sized	50 to 249 employees; binary variable
Large	250 employees and more; binary variable
Sector dummies	Ceramics, cement (reference: glass); binary variables
Country dummies	France, Italy, Poland, Spain, UK (reference: Germany); binary variables

Table 6 Descriptive statistics

Variable	*N*	Mean	Std. dev.	Min	Max
INNOPD_ICT1	247	0.473	0.044	0	2
INNOPD_ICT2	247	0.543	0.043	0	2
INNOPD_ICT3	247	0.613	0.043	0	2
INNOPC_ICT1	291	0.085	0.046	0	2
INNOPC_ICT2	291	0.749	0.046	0	2
INNOPC_ICT3	291	0.780	0.044	0	2
ICT_CRISISV	291	0.518	0.032		
ICT_budget	291	1.008	0.035	0	2
ICT_outsourcing	291	0.251	0.028	0	1
ICT_personnel	291	0.358	0.031	0	1
ICT_skill deficits	291	0.566	0.032	0	1
ICT_INFRA	291	0.307	0.018	0	1
ICT_NEWTECH	291	0.798	0.026	0	1
E_P	291	1.214	0.083	0	5
E_S	291	0.547	0.077	0	5
PCOMP	291	1.658	0.038	0	2
QCOMP	291	1.827	0.028	0	2
SCOMP	291	1.539	0.040	0	2
INTER	291	0.169	0.024	0	1
EXPORT	291	0.247	0.028	0	1
Medium-sized	291	0.383	0.031	0	1
	291	0.185	0.025	0	1

Table 7 Correlation matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 ICT_CRISIS	1.00														
2 ICT_budget	−0.22	1.00													
3 ICT_outsourcing	0.11	−0.05	1.00												
4 ICT_personnel	0.14	0.02	0.09	1.00											
5 E_P	0.11	0.11	0.08	0.07	1.00										
6 E_S	0.04	0.05	0.05	0.10	0.35	1.00									
7 ICT_NEWTECH	0.13	0.031	0.10	0.21	0.09	0.10	1.00								
8 ICT_INFRA	0.19	−0.09	0.09	0.19	0.12	0.10	0.32	1.00							
9 PCOMP	0.10	0.07	0.02	−0.09	0.14	0.01	−0.07	0.00	1.00						
10 QCOMP	−0.07	0.04	0.05	0.11	0.04	0.04	0.05	0.14	−0.00	1.00					
11 SCOMP	−0.07	0.03	−0.06	0.03	0.03	0.03	−0.00	−0.05	0.02	0.13	1.00				
12 INTER	0.15	−0.14	0.10	0.20	0.19	0.19	0.11	0.26	0.08	0.10	0.03	1.00			
13 EXPORT	0.04	0.04	0.07	0.00	0.20	0.20	0.02	0.08	−0.17	0.07	−0.08	−0.09	1.00		
14 Medium-sized	0.08	0.00	0.03	0.05	0.06	0.06	0.11	0.12	0.03	−0.09	−0.01	0.02	0.02	1.00	
15 Large	0.16	−0.04	0.10	0.30	0.09	0.09	0.09	0.27	−0.05	0.12	−0.14	0.25	0.15	−0.40	1.00

Table 8 First step of Rivers/Vuong test: probit estimates for ICT_CRISIS

	ICT_CRISIS
ICT inputs	
ICT_budget	− 0.718***
	(0.118)
ICT_outsourcing	0.084
	(0.149)
ICT_personnel	0.149
	(0.136)
ICT_skill deficits	0.314***
	(0.119)
ICT infrastructure	
E_P	0.042
	(0.054)
E_S	− 0.022
	(0.060)
ERP	0.081
	(0.143)
SCM	0.136
	(0.185)
SRM	0.122
	(0.201)
CRM	− 0.100
	(0.152)
CAD	0.103
	(0.121)
CAM	− 0.051
	(0.153)
SAAS	0.069
	(0.151)
ICT_NEWTECH	0.169***
	(0.041)
Market conditions	
PCOMP	0.295***
	(0.101)
QCOMP	− 0.169
	(0.117)
SCOMP	0.090
	(0.091)
Other firm characteristics	
INTER	0.205
	(0.174)
EXPORT	0.244*
	(0.149)

Table 8 (continued)

	ICT_CRISIS
Medium-sized	− 0.036
	(0.130)
Large	0.078
	(0.205)
Sector dummies (2)	Yes
Country dummies (5)	Yes
Const.	− 1.114***
	(0.372)
N	288
Wald chi^2	173.7***
Pseudo-R^2	0.192

Note: Heteroskedasticity-robust standard errors in brackets; ***. **, and * denote statistical significance at the 1, 5, and 10% test levels, respectively; reference for "medium-sized," "large": "small"

Table 9 Tests for joint effects

For equation in column 1 in Table 1 (INNOPD_ICT1):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel) = 0;
$Chi^2 = 9.16$; prob > $chi^2 = 0.000$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 16.3$; prob > $chi^2 = 0.000$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 1.60$; prob > $Chi^2 = 0.206$.
For equation in column 2 in Table 1 (INNOPD_ICT2):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel) = 0;
$Chi^2 = 4.13$; prob > $chi^2 = 0.042$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 6.92$; prob > $chi^2 = 0.009$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 4.01$; prob > $chi^2 = 0.045$.
For equation in column 3 in Table 1 (INNOPD_ICT3):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel = 0;
$Chi^2 = 1.18$; prob > $chi^2 = 0.277$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 4.8$; prob > $chi^2 = 0.028$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 4.09$; prob > $chi^2 = 0.043$.
For equation in column 1 in Table 2 (INNOPC_ICT1):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel = 0;
$Chi^2 = 3.28$; prob > $chi^2 = 0.070$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 30.89$; prob > $chi^2 = 0.000$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 0.28$; prob > $chi^2 = 0.597$.
For equation in column 2 in Table 2 (INNOPC_ICT2):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel = 0;
$Chi^2 = 7.90$; prob > $chi^2 = 0.005$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 13.74$; prob > $chi^2 = 0.000$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 0.32$; prob > $chi^2 = 0.569$.
For equation in column 3 in Table 2 (INNOPC_ICT3):
Coeff(ICT_budget) + coeff(ICT_outsourcing) + coeff(ICT_personnel = 0;
$Chi^2 = 10.38$; prob > $chi^2 = 0.001$;
Coeff(ICT_INFRA) + coeff(ICT_NEWTECH) + coeff(E_P) + coeff(E_S) = 0;
$Chi^2 = 27.93$; prob > $chi^2 = 0.000$;
Coeff(PCOMP) + coeff(QCOMP) + coeff(SCOMP) = 0;
$Chi^2 = 0.12$; prob > $chi^2 = 0.725$.

Note: coeff.: coefficients of the respective variables in Tables 3 and 4, respectively

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