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Strategic Complementarities Between Different Types of ICT–expenditures

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Non–technical summary

That "the whole is more than the sum of its parts" has been recognized by business economists for decades. It captures the very intuitive idea of synergies and system effects. If complementarities between firm strategies exist, this has major implications for the organization of firms (since complementarities require coordination which is often best achieved in hierarchical organizational structures) and for economic policy (since complementarities require investments in a multitude of strategies instead of a focussing on a single one).

This study uses cross–sectional data for German manufacturing and services to test whether strategic complementarities exist between four different types of ICT–expenditure components: (i) expenditures in physical ICT–capital (hardware, software and telecommunication equipment), (ii) expenditures for ICT–personnel (including freelance–workers), (iii) expenditures for ICT–services that are bought externally (e.g. programming services, fees paid to internet providers or payments to ICT–consultants) and (iv) 'other' (non–specified) ICT–expenditures. The main result is that evidence is found in favor of presence of strategic complementarities that cannot be explained by observed differences between firms with respect to firm size and sector affiliation, workforce qualification and firm's ICT–structure.

Strategic Complementarities Between Different Types of ICT–expenditures[§]

Ulrich Kaiser[*]

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Abstract: Multivariate Tobit models are estimated using German cross–sectional data to test whether strategic complementarities exist between expenditures in four different types of ICT–components. If two ICT–components are complements, they are correlated (provided that agents act rationally).
Significant correlations between all four types of ICT–expenditures are found and can neither be removed by 'standard' firm heterogeneity control variables such as firm size, firms' workforce qualification structure nor by firms' ICT–structure so that indication for the presence of complementarities is provided.
JEL classification: $C34, M11$
Keywords: strategic complementarity, ICT–investment, multivariate Tobit model

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1 Introduction

That "the whole is more than the sum of its parts" has been recognized by business economists for decades. It captures the very intuitive idea of synergies and system effects. Indeed, much theoretical and empirical research concerning these synergies between firm strategies has been completed in recent years. These papers basically focus on complementarities between (i) innovation strategies — as discussed by Arora and Gambardella (1990), Cassiman and Veugelers (2002), Cockburn and Henderson (1998) as well as Miravete and Pernias (2000) —, (ii) human resource practices — as discussed by Bertschek and Kaiser (2001) as well as Ichniowski et al. (1997) — and (iii) new technologies and the demand for heterogeneous labor — as surveyed by Chennels and van Reenen (1999).

Surprisingly, given the importance of information and communication technology (ICT) to date and the fact that economic theory, with the work of Milgrom and Roberts (1990), has laid the fundament for empirical research more than a decade ago, the relationship between different ICT–components has not been studied empirically so far. I aim at filling this gap by analyzing complementarities between four ICT–investment components using a large sample of German firms. The four ICT–expenditure components considered are: (i) expenditures in physical ICT–capital (hardware, software and telecommunication equipment), (ii) expenditure for ICT–personnel (including freelance–workers), (iii) expenditures for ICT–services that are bought externally (e.g. programming services, fees paid to internet providers or payments to ICT–consultants) and (iv) 'other' (non–specified) ICT–expenditures.

My empirical analysis is based on a large cross–sectional survey data set in German manufacturing industries and services. Multivariate Tobit models, econometric models that account for left–censoring of the ICT–expenditure levels (some firms do not invest in one or more ICT–components at all) and for the correlation between the unobserved (to the econometrician) factors that influence ICT–

spending, serve as the empirical tool in this analysis.

The identification of complementarities between firms' ICT–investment strategies is based on economic theory, namely on the theory of supermodularity and draws from Milgrom and Roberts (1990, 1995) as well as Holmström and Milgrom (1994). My exposition follows Cassiman and Veugelers (2002). Theory makes a main prediction that directly relates to the empirical identification of complementarities: if two forms of ICT–investments are complementary, they are positively correlated (if agents act rationally). This is a necessary condition for the existence of complementarity. A sufficient condition is that the two (or more) forms of ICT–investments remain being correlated if observed firm heterogeneity is considered. If adding variables representing firm heterogeneity help to remove the correlation between the ICT–investment components, these variables are the *sources* of complementarity. Strong evidence for the presence of complementarity is, however, only given if (and only if) *all* variables that might represent firm heterogeneity are taken into account and the correlations remain being significant. Although the empirical analysis controls for a wide range of unobserved firm heterogeneity variables, it is of course impossible to rule out that important factors, in particular unobserved influences such as management skills, are left out in the analysis.

Three sets of variables are used to control for observed heterogeneity: (i) 'standard' control variables such as sector affiliation and firm size, (ii) firms' workforce structure and (iii) firms' ICT–structure. Even though the 'standard' control variables and the variables representing firms' ICT–structure are highly significant in all equations and remove the correlation between the ICT–expenditures considerably, they are unable to fully reduce the correlation between the four ICT–expenditure equations. Hence, if (i) firms actually act rationally and (ii) my set of explanatory variables captures firm heterogeneity appropriately, evidence for the presence of complementarities between the four different ICT–expenditure components is found. This result remains even if ICT–expenditures scaled by sales or if ICT–expenditures per capita — instead of the natural logarithm of the level of ICT-expenditures — are used as the dependent variables.

The presence of complementarities between the different ICT–expenditures has an important implication for the organization of firms. As pointed out by Milgrom and Roberts (1995) , the presence of complementarities makes a point in favor of a hierarchical organization and disfavors a flat organizational structure since complementarities between firms' state variables calls for a coordination of efforts.

2 Theory

I base my empirical model on the theory of supermodularity, a powerful mathematical framework that allows to derive to the conditions for ICT–expenditures to be complementary. The point of departure is the following definition:

> **Definition:** Let A_i^k denote the $k = 1, \ldots, K$ activities that are undertaken by firm i. The profit function $\Pi(\boldsymbol{A_i})$ (with $\boldsymbol{A_i}= (A_i^1, \ldots, A_i^K)'$) is supermodular and A_i^k and A_i^{-k} are complements (substitutes) iff
>
> $$\frac{\partial^2 \Pi_i}{\partial A_i{}^k} \partial A_i^{-k} > 0 \quad \left(\frac{\partial^2 \Pi_i}{\partial A_i^k \partial A_i^{-k}} < 0 \right),$$
>
> i.e. investing in activity k has a higher incremental effect on revenue if it is also invested in activity $-k$ than if it is invested in activity k only.

The clearly first best approach to empirically uncover complementarities is to directly estimate the profit with activities A^k and A^{-k} and interactions of A^k and A^{-k} as explanatory variables to find an estimate of the cross–partials. However, profit data is reported by firms only on rare occasions such as in balance sheet data. If they are reported, then detailed information on firms' expenditures such as their spendings on different types of ICT–components are missing. Moreover, the 'direct' test for complementarities also requires data on prices for the k activities which are even harder to obtain on a firm–level basis. As shown by Athey and Stern (1998), complementarities can, however, also be detected using the below result that follows from the definition:

> **Result:** Let $\Pi(\boldsymbol{A_i},\boldsymbol{X_i})$ be supermodular in $(A_i^k, \boldsymbol{X_i})$, and let $\boldsymbol{X_i}$ be a vector of exogenous variables that represent firm heterogeneity. Then $A_i^*(\boldsymbol{X_i}) = (A_i^{k^*}(\boldsymbol{X_i}), A_i^{-k^*}(\boldsymbol{X_i}))$ — the optimal choice of alternatives — is monotone non–decreasing in $\boldsymbol{X_i}$. In a cross–sectional study, $A_i^k(\boldsymbol{X_i})$ and $A_i^{-k}(\boldsymbol{X_i})$ will then be positively correlated.

The result states that expenditures in one activity is a complement to another activity if the expenditure levels are correlated (once again: provided that agents act rationally) — s ee Holmström and Milgrom (1994, part B) for an additional reference. This is a necessary condition for the presence of complementarity. Due to heterogeneity across firms, the correlation between the investment expenditures decisions could be biased and lead to a false acceptance of the hypothesis of complementarity, as pointed out by Athey and Stern (1998). For example, large firms are likely to have large expenditures in all four types of ICT–expenditures. Consequently, if it is not controlled for firm size, all four types of ICT–expenditures will be highly correlated. This correlation would, however, be 'spurious' since it might be primarily caused by firm size.

Indeed, if variables that represent firm heterogeneity are added and if adding these variables removes the correlation between the activities, these added variables are the *sources* of complementarity.

Cross–sectional analyzes such as the present one can only take into account *observed* firm heterogeneity. There might of course also be a significant *unobserved* heterogeneity, for example due to differences in managements' abilities and backgrounds. For example, a CEO with a degree in computer sciences is likely to follow a very different ICT–strategy than a former carpenter. As a consequence, we might find complementarities that are caused by these unobserved differences in firms' management. Panel data can potentially take care of these effects, at least if we believe that these effects are time–invariant (implying i.a. that management does not change). The data used here are cross–sectional only so that panel data estimation is not an option.

3 Data

The data stem from a computer aided telephone interview survey by *infas Sozialforschung*, Bonn, Germany, in commissioned work for the Centre for European Economic Research (Zentrum für Europäische Wirtschaftsforschung, ZEW), Mannheim. The firms contacted were randomly drawn from a stratified sample of about 11,000 German firms. The sample was stratified with respect to sector affiliation, firm size and region (East/West Germany). Only firms with at least five employees were included in the survey. The sample was drawn from data material made available by Germany's largest credit rating agency Creditreform. Creditreform has the most comprehensive database of German firms at its disposal. The survey was conducted in fall 2000. About 4,400 firms participated in the survey, which corresponds to a response rate of approximately 43%. After performing consistency checks, due to item non–response in the dependent and explanatory variables in the empirical model, and due to leaving out the ICT–producing sector (139 are lost by dropping these firms) in the estimation I am left with 1,853 firms in the empirical analysis.

The data set used in this study is confidential. The ZEW does, however, grant researchers who wish to use the data for scientific purposes access upon request.[1] Most of the observations are lost due to item–nonresponse in the ICT–expenditure

[1]Send inquiries to `info@zew.de`.

variables. An item–nonresponse analysis shows that these observation might not be missing at random. I estimated a binary probit model with the incident of item–nonresponse as dependent variable. Explanatory variables were sector affiliation, the natural logarithm of the number of employees and its square as well as regional affiliation. In particular, large firms are significantly *less* likely to report ICT–expenditures broken down into the four different components (expenditures in physical ICT–capital, expenditure for ICT–personnel, expenditures for ICT–services that are bought externally and 'other' ICT–expenditures).
The incidence of not responding to the ICT–questions might hence be correlated with the level of ICT–expenditures so that a classical sample selection bias problem occurs that leads to inconsistent parameter estimates. Such a problem can be overcome by estimating Tobit models with sample selection; see e.g. Greene (1995, Sect. 27.3) for a reference. The baseline idea is to simultaneously estimate a binary probit model for item–nonresponse and a Tobit model for the level of ICT–expenditures. I proceeded this way and estimated separate Tobit models with sample selection for all four ICT–expenditure components. Explanatory variables in the ICT–expenditure equations were the same as in the 'full' specification that includes all three sets of explanatory variables as discussed in Section 4. The item–nonresponse equation was specified by sector dummy variables, the natural logarithm of the number of employees and its square, regional affiliation and a set of dummy variables indicating the position of the respondent to the survey in the firm. The latter variables are my 'exclusion restrictions' as they are termed in econometrics (the non-response behavior of respondents differs with their position but it does at the same time not have an effect on ICT–expenditures). The correlation between the ICT–expenditure equations and the item–nonresponse equations was insignificantly different from zero so that evidence is given that the observations are missing at random.

4 Econometrics and results

4.1 Econometrics

Table 1 displays descriptive statistics of the four ICT–expenditure levels. Since the absolute values are not very informative, they are also set in relation to total ICT expenditures and to workforce size. Appendix A displays descriptive statistics of the level of ICT expenditures. Expenditures in physical ICT capital possesses, with almost 50 per cent, the largest share in total ICT expenditures, followed — with a large distance — by expenditures for ICT–personnel, ICT–services and 'other' ICT–expenditures. The same order and qualitative differences hold for ICT expenditures per capita as well. They also show up in the share of zero spendings for individual ICT–components: there is almost no left–censoring for expenditures in physical ICT–capital but severe left–censoring in the 'other' components. The amount of all four ICT–expenditure components varies considerably across firms and ICT–expenditures per capita are also heavily skewed to the right. This is why I use the natural logarithm of the ICT–spending components as the dependent variable in the econometric analysis.[2] Taking natural logarithms accounts for modest outliers and also transforms the expenditure levels in normally distributed variables.[3] Normality of the error terms is crucial for the Tobit model to produce consistent parameter estimates.

The left–censoring of the dependent variables forbids to directly correlate the four ICT–expenditure components to one another. I therefore use multivariate Tobit models, as thoroughly described by Lee (1992), to calculate the correlation coefficients between the four ICT–spending levels. The idea of the multivariate

[2] All ICT–expenditure levels were added by one to avoid taking the natural logarithm of zero.

[3] Kernel density estimation (Härdle 1989) applied to those ICT–expenditure values larger than zero shows that the approximate distribution of the ICT–expenditure components is normal.

Tobit model is to jointly estimate a multi–equation Tobit model that allows for the error terms of each equation to be correlated. Separate estimation generates consistent but, if the error terms are truly correlated, inefficient parameter estimates. In the present case, I do not worry so much about estimation efficiency but I am interested in the correlation between the error terms of the ICT–expenditure equations — which simply is the correlation of the ICT–expenditure levels if it is not accounted for explanatory variables other than a constant term — so that using a multivariate Tobit model is a natural choice.

4.2 Results

4.2.1 Univariate correlations

The empirical analysis starts with calculating simple correlation coefficients between the log ICT–expenditure levels. Correlation results are displayed in Table . All correlation coefficients are highly significantly different from zero and positive. Hence, the necessary condition for the four ICT–expenditure levels to be complementary is satisfied.

The correlations are particularly large between physical ICT–capital and labor cost for ICT personnel, between physical ICT–capital and ICT–services as well as — to a lesser extent — between labor cost for ICT personnel and ICT–services. They are less pronounced between 'other' ICT–expenditures and the remaining three types of ICT–expenditures. These results clearly indicate that investment in one type of ICT–component is very likely to be associated with investment in another ICT–component.

The correlation coefficients also translate into changes of expenditures in one ICT–component due to an unanticipated change another ICT–component For example, a shock in the expenditures for ICT–capital of 6.907 DM (or ln(1,000) DM) for ICT–capital is associated with an increase in expenditures in labor cost for ICT personnel of $0.5630 \cdot \ln(1{,}000)$ DM = 3.8891 DM.

Now that the necessary condition for complementarity is established, I turn to the sufficient condition: ICT–expenditure levels need still to be correlated if it is accounted for observable firm heterogeneity (and possibly for unobserved firm heterogeneity).

4.2.2 Multivariate correlations

Explanatory variables

I include three sets of variables that account for heterogeneity across firms: (i) 'standard' control variables that are used in almost every empirical firm–level analysis, (ii) variables that represent firms' skill mix and (iii) variables that represent firms' ICT–structure mix.

'Standard' controls: This set of variables accounts for differences of firms from different sectors, firm size, firms' regional affiliation and firm age. Apparently, there should be significant differences between firms from different sectors so that I include of twelve dummy variables for sector affiliation: Manufacture of metallic products and machinery equipment, Manufacture of chemical products, Manufacture of basic chemical products, Manufacture of electrical equipment, Manufacture of instruments, Manufacture of motor vehicles, Wholesale trade, Retail trade, Transport, Banking and insurance, Architectural and engineering services and 'Other' business–related services (e.g. advertising, vehicle renting etc.) with Manufacture of consumer products as base category. Likewise for firm size: larger firms will spend more on the ICT–components than smaller firms. There could also be a nonlinear relationship that my specification allows for by including both the natural logarithm of firm size and its square. It is well known that ICT–expenditures for East German firms is lower than that of West entities so that I include a dummy variable for East German firms in the specification to pick up this effect. Two dummy variables for being part of a larger conglomerate

and for having a foreign parent firm are also included in the specification. To sum up, the 'standard' control variables take care of 'spurious' correlations between ICT–expenditure levels that are simply due to differences between sectors and regional affiliation as well as to differences in firm size.

Skill mix: It is well known that high skilled labor and ICT are complements. Consequently, a high correlation between ICT–expenditure types could be due to this complementarity between high skilled labor and ICT. I thus include the share of (i) technical college graduates, (ii) workers with completed vocational and additional technical training, (iii) workers with completed vocational training, (iv) apprenticeship trainees and (v) workers without formal qualification. The share of workers with completed vocational training (but with no additional training) forms the comparison group. Employing a large share of university graduates does not necessarily mean that a firm also employs a large fraction of workers that is qualified for fulfilling ICT–related tasks. I therefore additionally include the share of ICT–workers in total workforce.[4]

ICT–structure: A high correlation between different types of ICT–expenditures can clearly be due to similarities in firms' ICT–structure. If a firm, for example, uses many different ICT–applications, it is more likely to invest in different types of ICT than a firm than only uses e–mail. To control for differences in firms ICT–structure, I include three different subsets of variables. The first subset of variables captures ICT–usage by the workforce and consist of the following variables: number of PCs per workplace, share of interconnected PCs, share of workers that spend most of the working time at a PC and the share of workers with internet access from their workplaces.

The second subset of explanatory variables represents firms use of software and the internet and includes dummy variables for either 'wide' use or 'no' use (with 'rare' use as base category) of office software packages; software for data

[4]Note that the share of ICT–workers and the share of university graduates are only modestly correlated with a correlation coefficient of 0.2381.

banks; software for business controlling and planning; Computer Aided Design, Computer Aided Manufacturing or Computer Aided Engineering software (CAD/CAM/CAE software); electronic data interchange software and email–exchange software. Internet usage is taken into account by a variable that measures how many internet–related activities are undertaken by the firms. The questionnaire breaks internet usage down into eight different categories: information search and communication; advertising and marketing; sales of products and services to end consumers over the internet (B2C e–commerce); sales of products and services to other firms the internet (B2B e–commerce); ordering of products and services over the internet; internet banking; communication with customers over the internet and personnel recruiting over the internet. My variable ‘internet’ simply counts how many of these internet activities are pursued by the firms. Its value hence ranges from 0 to eight. The subset of firm heterogeneity variables representing software and internet use also includes a dummy variable for ICT–outsourcing since recent work by Henkel and Kaiser (2003) has underscored the strategic importance of ICT–outsourcing for firms.

The third subset of variables representing ICT–structure captures obstacles to the diffusion and adoption of ICT since these hampering factors might have the same influence on each of the four ICT–expenditure components so that leaving them out leads to correlation in the error terms. The questionnaire asks for seven different obstacles to the diffusion of ICT: too high setup and running cost, lack of financial resources, lack of ICT–workers, internal resistance against ICT, no need for ICT–applications, difficulties in the introduction of ICT and juridical insecureness (e.g. with respect to e–commerce). My specification includes seven dummy variables for each of the obstacles that are coded one if the respective obstacle was a factor that hampers ICT–adoption and diffusion.

There might of course be a problem of endogeneity related to the ICT–structure variables. Although it is straightforward to write the estimation problem in terms of moment conditions and to estimate the system of equations using GMM, it is much harder — and even impossible given the data at hand — to find appropriate instruments for the potentially endogenous variables. Since the main interest is in correlations and not on causalities endogeneity is a minor problem here, however. Moreover, as it will turn out later, the ICT–structure variable have modest effects on the reduction of correlations between the ICT–components which clearly does not suggest that severe endogeneity problems are present.

Appendix A provides descriptive statistics for the variables involved in the estimation.

The empirical strategy is to successively add explanatory variable to the estimation equations. I then check to what extent adding the explanatory variables reduces the correlation between unobserved components of the ICT–expenditure equations (i.e. the error terms correlation between the error terms). There are seven possibilities to combine the three different sets of explanatory variables: (i) adding 'standard' firm heterogeneity controls only, (ii) adding skill structure only, (iii) adding ICT–structure only, (iv) adding 'standard' firm heterogeneity and skill structure, (v) adding skill structure variables and ICT–structure, (vi) adding 'standard' firm heterogeneity and ICT–structure and (vii) adding all three sets of control variables.

Results

Since the key interest is in the correlation between the four ICT–expenditure levels, I only display the estimation results for the 'full model' — the model containing the complete set of explanatory variables. This presentation is moved to Appendix B. The results for the sub–sets of explanatory variables differ qualitatively very little from the ones of the full model. Most variables have the same qualitative effect on all four equations: (i) larger firms spend significantly more on ICT–components than smaller firms, (ii) the larger the share of ICT–workers is, the more firms spend on ICT components, (iii) the higher the number of PCs per workplace, the more firms spend on ICT–components, (iv) the more internet applications are used, the more firms spend on ICT–components and (v) ICT–

outsourcing firms spend more on ICT–components than non–outsourcing firms. The 'standard' control variables and the ICT–structure variables are jointly highly significantly different from zero in all four equations. By contrast, the skill mix variables matter significantly only in the labor cost for ICT–personnel equation. The variation of ICT–expenditures, as measured by the standard error of the error term (denoted by σ in Table B), differs considerably across the ICT–components. It is largest for 'other' ICT with a standard deviation of 4.8018. It is much smaller for ICT–capital (1.9096), for ICT–services (2.4316) and for ICT–personnel (4.6286).

While the original estimation results displayed in Table B are of secondary interest only, Table 3 and Table 4 are of major importance for the present analysis. Table 3 shows the absolute value of the correlation coefficients if all explanatory variables are added to the estimation, this is the case where the reduction in correlation is largest. Table 4 displays the percentage reduction in the correlation coefficients relative to the 'pure' correlations coefficients that did not account for firm heterogeneity.

The key result of Table 3 is that the ICT–expenditure levels are still highly significantly correlated with one another. One exception is the correlation between ICT–capital and 'other' ICT which is insignificant. This indicates that there neither is complementarity nor substitutability between these ICT–components. In general, however, evidence is given that the four ICT–components are indeed complements — at least if we want to believe that firms act rationally (which we usually do) and that the firm heterogeneity variables adequately capture difference across firms (which clearly is always debatable).

The correlation again is particularly strong between physical ICT–capital and labor cost for ICT–personnel as well as between, to a lesser extent, labor cost for ICT–personnel and ICT–services. The combinations including the 'other' ICT–component are, by contrast, characterized by modest correlations. This is again due to the fact that 'other' is not a well–defined ICT–spending category.

What does this result imply for strategic management? It is obvious that it means that instead of focussing on one type of ICT–components, for example on ICT–hardware alone, firms should invest in all ICT–components. Firms fully benefit from their ICT–investments only if one type of ICT–spending is joined by a bundle of accompanying expenditures. This is somewhat in contrast to current business practice especially among very small enterprizes that tend to invest in one ICT–component but do not make the complementary investments (Licht et al. 2002). At a less general level, these results make a point in favor of a hierarchical organizational structure since making complementary investments requires a high degree of coordination. According to Milgrom and Roberts (1995) this makes hierarchical structures preferable over flat ones since coordination cost are lower.

Complementarities between ICT–components also has clear implications for ICT–policies. It indicates that governments should promote a bundle of ICT–diffusion enhancement measures instead for focussing on one measure, most often the diffusion of the internet, only.[5]

What are drivers of the complementarities? Although unable to fully explain it, those variables that markedly reduce the correlation between the ICT–expenditure levels are sources of the initial complementarity. The most pronounced contribution — leaving out the reductions in the correlations that involve the 'other' ICT category — to the reduction in the correlation between the ICT–expenditure level is due to the 'standard' observable firm heterogeneity variables. The reduc-

[5] For example, the German Federal Ministries for Economics and Technology (Bundesministerium für Wirtschaft und Technologie, BMWi) as well as for Education and Research (Bundesministerium für Bildung und Forschung, BMBF) recently published a list of ten targets with respect to Germany's competitive position in ICT that should be reached until 2005 (BMWi/BMBF 1999). Seven of these targets are directly related to the diffusion and technical improvement of the internet. The other three targets concerns the promotion of multi–media firms, the development of a supervisory framework for firms operating in ICT and media and the enhancement of apprenticeship training in ICT–related professions.

tion is between 19 (ICT–hardware/ICT–labor) and 34 per cent (ICT–labor/ICT–services). Neither the set of skill structure variables nor the ICT–structure variables can to an equally large extent explain the initial correlations.

The contribution of firms' skill structure is astonishingly small. If considered separately from the other two sets of control variables, the reduction in correlation is close to zero. It's contribution to the reduction in correlation is also very small if it is used in combination with the other sets of explanatory variables. This shows that a highly skilled workforce does not necessarily go along with large spendings on different types of ICT.

Firms' ICT–structure by contrast makes a considerable contribution to the reduction in the initial complementarity levels. Taken alone, it reduces correlations by between eight and 20 per cent. If used in addition to the 'standard' control variables, it's marginal contribution is reduced. This indicates that parts of the ICT–structure's effect is absorbed by accounting for sector–specific differences and firm size.

Goodness of fit

Only the 'other' ICT–expenditure equation is poorly fitted as indicated by a particularly low pseudo R^2 of 0.0466. The pseudo R^2 is, just as for the other equations, calculated from separate Tobit–estimations. The specification is, however, jointly highly significant from zero as demonstrated by a Wald test for joint signiifcance. The pseudo R^2 of the physical ICT–expenditure equation is 0.0952, that of the labor cost for ICT–personnel is 0.1149 and that of ICT–services is 0.0821. The overall R^2 of the multivariate Tobit model is 0.0847. All four equations are also highly significant. With regard to the high variation of ICT–expenditures across firms, as shown by the values of the σ–parameters displayed in Table B, these values indicate a good explanatory power of the estimations.

An indirect test of the robustness of the estimation results is that the quantitative results, most importantly the results with respect to the reduction of the correlation between the ICT–expenditure levels remains the same even if ICT–

expenditures are scaled by the number of employees or by total sales. The only exception is the case of scaling by the number of employees where the correlation coefficients between 'other' ICT–expenditures and ICT–capital as well as ICT–labor become insignificantly different from zero.

5 Summary and conclusions

This paper shows that the unobserved (to the econometrician) components of the following four different types of ICT–expenditures are highly correlated with one another even if it is controlled for a large set of variables that represent firm heterogeneity: investment in physical ICT–capital, labor cost for ICT–personnel, expenditures for ICT–services that are bought externally and 'other' ICT–expenditures. Provided that (i) firms act rationally (which is something that economists are inclined to believe) and (ii) the variables representing firm heterogeneity are adequate (which is an issue that economists will disagree about), these results point at the presence of strategic complementarities between the four different ICT–expenditures.

The empirical evidence is provided for a large sample of firms from German manufacturing and services. The correlations are particularly pronounced between physical ICT–capital and labor cost for ICT–personnel as well as — to a lesser extent — between labor cost for ICT–personnel and ICT–services. Combinations that involve the 'other' ICT–component are characterized by modest correlations. This is due to the fact that 'other' expenditures comprise of a multitude of heterogeneous ICT–spendings.

A large part of the complementarity is attributable to firms' sectoral affiliation and to firm size. Adding these variables leads to a decrease in correlations of up to 34 per cent. Firms' ICT–structure reduces the correlation coefficients by up to 20 per cent. By contrast, the workforces' skill levels and the share of ICT–workers in total employment, has an almost negligible explanatory power.

The strategic management implication of the presence of complementarities between ICT–expenditure levels is that firms need to invest into a bundle of (complementary) ICT–component to fully reap the benefits of their investments. This bundling of efforts might by easier achieved if organizational structures are hierarchical as pointed out by Milgrom and Roberts (1995). The economic policy implication of strategic complementarities is that governments should invest in a bundle of ICT–promotion measures instead of focussing on specific subgroups such as, for example, the diffusion and improvement of the internet.

It is important to bear in mind that the evidence for complementarity provided here is an indirect one. It measures the correlation between ICT–expenditures assuming that firms behave optimally. A direct approach would be to estimate the effects of the different types of ICT–expenditures on the firms' revenue function. Given the apparent measurement problems, proceeding this way is, however, not an option of large scale econometric analyzes.

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Table 1: ICT–expenditures by type

Share in total ICT–exp. (in %)				
	ICT–phys.	ICT–pers.	ICT–serv.	ICT–other
Share exp.=0	4.7	22.3	27.2	64.5
Share in total ICT–expenditures (in %)				
Mean	47.4	7.3	3.8	0.8
Median	3.6	1.7	0.9	0.0
Std. dev.	25.7	20.9	11.4	2.1
Per capita (in 1,000 DM p.c.)				
Mean	3.9	1.9	1.0	0.2
Median	1.0	4.8	0.3	0.0
Std. dev.	14.3	4.8	2.4	0.6

Note: the abbreviations are as follows: 'Share exp.=0' — share of firms with zero expenditures in the respective ICT–component; 'ICT–phys.' — expenditures in physical ICT–capital; 'ICT–pers' — expenditures for ICT personnel; 'ICT–serv.' — expenditures for externally bought ICT–services; 'ICT–other' — expenditures for other ICT–components. Number of observations: 1,815.

Table 2: Univariate correlation coefficients between ICT–expenditure components

	ICT–physical	ICT–pers.	ICT–serv.	ICT–other
ICT–physical	1			
ICT–personnel	0.7323	1		
ICT–services	0.6197	0.6041	1	
ICT–other	0.2220	0.3000	0.3395	1

Note: the abbreviations are as follows: 'ICT–phys.' — expenditures in physical ICT–capital; 'ICT–pers' — expenditures for ICT personnel; 'ICT–serv.' — expenditures for externally bought ICT–services; 'ICT–other' — expenditures for other ICT–components. The correlation coefficients are estimated from multivariate Tobit models and they are all highly significantly different from zero. Number of observations: 1,378.

Table 3: Multivariate correlation coefficients between ICT–expenditure components

	ICT–physical	ICT–pers.	ICT–serv.	ICT–other
ICT–physical	1			
ICT–personnel	0.5630	1		
ICT–services	0.4408	0.3494	1	
ICT–other	-0.0007	0.0754	0.1515	1

Note: the abbreviations are as follows: 'ICT–phys.' — expenditures in physical ICT–capital; 'ICT–pers' — expenditures for ICT personnel; 'ICT–serv.' — expenditures for externally bought ICT–services; 'ICT–other' — expenditures for other ICT–components. The correlation coefficients are estimated from multivariate Tobit models and they are all highly significantly different from zero except for the correlation between 'ICT–phys.' and 'ICT–other' which is insignificant as well as between 'ICT–pers.' and 'ICT–other' which is significant at the five per cent significance level. Number of observations: 1,378.

Table 4: Change in correlations due to adding explanatory variables (in per cent)

Adding 'standard' firm heterogeneity controls only			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-18.8678	n.a.	
ICT–services	-24.9891	-34.1952	n.a.
ICT–other	-86.2628	-61.5334	-43.6599
Adding skill structure only			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-0.9090	n.a.	
ICT–services	-0.4506	-4.4030	n.a.
ICT–other	-3.0322	-2.6247	-2.2217
Adding ICT–structure only			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-7.6982	n.a.	
ICT–services	-11.2591	-19.9600	n.a.
ICT–other	-33.8025	-27.6814	-23.7856
Adding 'standard' firm heterogeneity and skill structure			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-20.4719	n.a.	
ICT–services	-25.4875	-35.0159	n.a.
ICT–other	-87.7869	-62.4340	-43.6260
Adding skill structure variables and ICT–structure			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-7.9035	n.a.	
ICT–services	-10.9336	-19.6349	n.a.
ICT–other	-35.4440	-29.2528	-25.8300
Adding 'standard' firm heterogeneity and ICT–structure			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-22.6961	n.a.	
ICT–services	-29.4492	-42.7177	n.a.
ICT–other	-100.3638	-75.0068	-55.0966
Adding all three sets of control variables			
	ICT–physical	ICT–labor	ICT–services
ICT–labor	-23.1182	n.a.	
ICT–services	-28.8717	-42.1640	n.a.
ICT–other	-100.3130	-74.8603	-55.3614

Note: the abbreviations are as follows: 'ICT–phys.' — expenditures in physical ICT–capital; 'ICT–pers' — expenditures for ICT personnel; 'ICT–serv.' — expenditures for externally bought ICT–services; 'ICT–other' — expenditures for other ICT–components. The table show the percentage change in the correlation coefficients due to adding explanatory variables to the ICT–expenditure equations. Number of observations: 1,378.

Appendix A: descriptive statistics

	Mean	Median	Std. dev.
Dependent variables			
ln(ICT–physical+1)	4.7427	4.3944	2.4073
ln(ICT–labor+1)	4.0055	3.9318	2.8765
ln(ICT–services+1)	3.3512	3.0445	2.7947
ln(ICT–other+1)	1.6563	0.0000	2.5340
Explanatory variables			
'Standard' controls			
Sector dummies			
Manufacture of metallic products and machinery equipment	0.0835		
Manufacture of chemical products	0.0515		
Manufacture of basic chemical products	0.0987		
Manufacture of electrical equipment	0.0399		
Manufacture of instruments	0.0392		
Manufacture of motor vehicles	0.0958		
Wholesale trade	0.0602		
Retail trade	0.0733		
Transport	0.0849		
Banking and insurance	0.0675		
Architectural and engineering services	0.1074		
'Other' business–related services	0.0864		
Other			
East Germany	0.1959		0.3971
Conglomerate member	0.3788		0.4853
Foreign parent	0.1967		0.3976
Firm size			
ln(# of employees)	4.5815	4.3820	1.5597
ln(# of employees)^2	23.4215	19.2022	15.9911
Skill structure			
Share technical college graduates	0.0944	0.0600	0.1153
Share voc. and techn. training	0.1517	0.1136	0.1446
Share vocational training	0.4452	0.4806	0.2227
Share apprenticeship trainees	0.1587	0.1193	0.1650
Share no formal qualification	0.0485	0.0455	0.0414
Share ICT–workers	0.0290	0.0075	0.0849

Appendix A: descriptive statistics (continued)

	Mean	Median	Std. dev.
ICT structure			
PCs per workplace	0.4795	0.3571	0.3662
Share of interconnected PCs	85.0363	100.0000	28.1041
Share of workers most time at PC	41.2961	30.0000	31.1305
Wide use office software	0.8541		0.3531
No use office software	0.0138		0.1167
Wide use of data bank software	0.3955		0.4891
No use of data bank software	0.1567		0.3637
Wide use of business controlling software	0.3737		0.4840
No use of business controlling software	0.1713		0.3769
CAD/CAM/CAE software	0.1952		0.3965
CAD/CAM/CAE software	0.4231		0.4942
Wide use of electronic data interchange software	0.0791		0.2700
No use of electronic data interchange software	0.5392		0.4986
Wide use of email–exchange software	0.6219		0.4851
No use of email–exchange software	0.0653		0.2472
Internet access per capita	26.8084	10.0000	31.8331
Score of internet applications use	2.2939	2.0000	1.2800
Outsourcing of ICT	0.9492		0.2197
Hampering factor cost	0.1125		0.3161
Hampering factor finance	0.0486		0.2152
Hampering factor personnel	0.1734		0.3788
Hampering factor internal resistance	0.0660		0.2484
Hampering factor no need	0.0406		0.1975
Hampering factor technology	0.1335		0.3403
Hampering factor law	0.0573		0.2326

Appendix B: Multivariate Tobit estimation results

	ln(ICT–physical) Coeff.	ln(ICT–labor) Coeff.	ln(ICT–services) Coeff.	ln(ICT–other) Coeff.
Constant	0.1020	-2.7512**	-4.1943***	-7.9780***
Man. of metallic products	-0.0460	-0.1596	-0.2257	1.0434
Man. of chemical products	0.0246	0.1498	-0.1394	1.3842*
Man. of basic chemical products	-0.2756	-0.1271	0.0565	-0.0849
Man. of electrical equipment	0.2102	0.2606	-0.0564	-0.0608
Man. of instruments	-0.0424	-0.3029	-0.5412	0.0247
Man. of motor vehicles	0.0669	-0.1741	-0.0462	-0.6557
Wholesale trade	-0.2251	-0.3204	-0.4901	0.9987
Retail trade	-0.0719	-0.3828	-0.4340	-0.6085
Transport	-0.0765	0.0912	-0.4683	-0.1258
Banking and insurance	-0.0486	0.3189	0.3656	0.4718
Arch. and eng. serv.	-0.1933	-0.3180	-0.3028	0.6438
'Other' business–rel. serv.	-0.2025	-0.1066	-0.1094	1.6474**
East Germany	-0.1662	-0.0970	-0.4650**	-0.3713
ln(# of employees)	0.6408***	1.1847***	0.7957***	0.3255
ln(# of employees)^2	0.0203	-0.0067	0.0109	0.0681*
Conglomerate member	-0.0511	0.0065	-0.1959	-0.6126*
Foreign parent	0.2084	0.3431	0.3750	0.1995
Share tech. college grad.	0.2110	0.5872	1.1772	-0.0831
Share voc. and techn. training	-0.5848	-0.1617	1.2386	0.2273
Share vocational training	-0.4752	-0.4425	1.3279*	1.9499
Share apprenticeship trainees	-0.9209	-1.1322	1.4674	1.4559
Share no formal qualification	-0.7933	-5.8882***	0.3893	0.3057
Share ICT–workers	1.5184**	2.4992***	0.1896	1.3223
PCs per workplace	1.1865***	1.6543***	1.7286***	1.9612***
Share interconnected PCs	0.0041*	0.0063**	0.0004	0.0027
Share workers most time at PC	0.0013	0.0007	-0.0014	-0.0092
Wide use office software	0.2450	0.0401	0.2797	0.0321
No use office software	0.9702***	0.1575	-0.7616	-0.5912
Wide use of data bank softw.	0.0523	-0.0878	0.0449	-0.3408
No use of data bank softw.	0.1718	-0.1856	-0.3995	-0.0551
Wide use of business softw.	-0.2925**	-0.2191	-0.1733	0.2603
No use of business softw.	-0.2903*	-0.2094	-0.5031**	-0.4317

Appendix B: Multivariate Tobit estimation results (continued)

	ln(ICT–physical) Coeff.	ln(ICT–labor) Coeff.	ln(ICT–services) Coeff.	ln(ICT–other) Coeff.
CAD/CAM/CAE software	-0.0518	-0.4809**	-0.5517**	-0.3068
CAD/CAM/CAE software	-0.2143	-0.3461*	-0.2123	-0.2625
Wide use of EDI software	0.0751	-0.0295	-0.3379	-0.9268
No use of EDI software	0.1030	-0.1273	-0.4421**	0.0362
Wide use of email software	0.1505	0.2359	0.0786	1.1914***
No use of email software	-0.1133	-0.0670	-0.5381	-1.0617
Internet access per capita	-0.0031	-0.0041	0.0026	0.0076
Score internet applications use	0.1167**	0.1061	0.0610	-0.3458***
Outsourcing of ICT	0.4466	0.7250**	1.9334***	2.0460**
Hampering factor cost	-0.3029	-0.0391	-0.4726	0.6055
Hampering factor finance	0.1643	0.0257	0.4561	0.6221
Hampering factor personnel	-0.2215	0.0759	-0.2595	-0.2810
Hampering factor internal resistance	0.4272	0.1150	0.2151	-0.9561
Hampering factor no need	-0.1334	-0.4466	-0.7171*	0.0895
Hampering factor technology	0.2332	0.0335	0.2242	0.5776
Hampering factor law	-0.0223	0.3702	0.5828	1.0229
σ	1.9096	2.4316	2.6582	4.6286
Pseudo R^2	0.1088	0.1123	0.0900	0.0492

Note: the abbreviations are as follows: 'ICT–phys.' — expenditures in physical ICT–capital; 'ICT–labor' — expenditures for ICT personnel; 'ICT–serv.' — expenditures for externally bought ICT–services; 'ICT–other' — expenditures for other ICT–components. The asterikses ***, ** and * denote significance at the one, five and ten per cent significance level respectively. Number of observations: 1,378. The pseudo R^2 of the entire specification is 0.0847.