PRELIMINARY DRAFT
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Simultaneous adoption of technologies: Descriptive cross-country evidence from Europe[a]

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The adoption and investment in new technologies is seen as an important driver of firm performance. Using linked micro-data from 15 European countries we document empirical evidence on the individual and joint adoption of different types of innovation (product, process, organizational and marketing) and different types of Information and Communication Technologies (ICTs), varying from mobile internet connection to IT systems as Enterprise Resource Planning, Supply Chain Management and Customer Relation Management (ERP, SCM, CRM) software suites. We identify differences between countries and sectors. Overall there is evidence of a substantial amount of joint adoption of, and therefore a positive dependence between, different new technologies. We present a more rigorous analysis of joint adoption using microdata from the Netherlands. Using a novel methodological approach we estimate bivariate models of adoption, where the decision with respect to one adoption is affected by the decision with respect to another adoption. We find significant positive dependence between the adoption of IT systems and product and organizational innovation, but less so in the case of process innovation. The finding of positive dependence is consistent with at least two theories about firm investment decisions: complementarities in firm strategies and advantages in adjustment costs of simultaneous adjustment. We briefly discuss the intuition of these theories.

Keywords: ICT, innovation, e-business, adoption, complementarities, adjustment costs

[a] This paper contains results from the ESSLimit database. Currently this database is still under construction and figures are preliminary and should not be quoted. Moreover, due to various methodological deviations figures may not necessarily match officially published national totals and should not be treated as such.

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1. Introduction

In a competitive industry it is imperative for each firm to stay ahead of its competitors to stay in business. Less productive firms are pushed out of the market, and are replaced by more productive new-comers, or market shares are seized by incumbent firms that are more efficient (Bartelsman and Doms, 2000). In line with the Schumpetarian view on economic growth, the adoption and investment in new technologies is seen as an important driver of firm performance. The adoption of new technologies offers firms the opportunity to distinguish themselves from competitors, and successful implementation will translate in higher productivity and better chances of survival and/or increased market shares.

In this paper, we present cross-country evidence on the adoption of a selection of new technologies. We consider innovation (product, process, organizational, and marketing), and the adoption of mobile internet and e-business ICT systems (Enterprise Resource Planning, ERP, Customer Resource Planning, CRM, and Supply Chain Management, SCM). There is a large literature on the productivity effects of both innovation and ICT (see Van Leeuwen, 2008). In this literature, it is also suggested that adoption of a new technology by itself may not be directly beneficial, but that a firm should consider the adoption decision of a certain technology simultaneous with the decision about another technology (Milgrom and Roberts, 1995). The idea is that the introduction of a new technology must be backed up by other changes in the firm. A change to a new management structure that allows workers to have more responsibilities, for example, could benefit from the introduction of an ICT system that allows the monitoring of decisions by workers. Evidence on complementarities between ICT and organizational changes is presented in amongst others the work by Brynjolfsson and Hitt (2000). Moreover, ICT is sometimes seen as a general purpose technology that enables innovation (Spiezia, 2011).

Another line of research observes that adoption, investment and any other changes implied by firm decisions, is costly for the firm. For example, the implementation of new ICT may require learning by workers or (re)training, and disruption to the production process due to 'child diseases' or unforeseen non-compatibilities. If there is a joint component in these so-called adjustment costs, then firms have an incentive to make these adjustments simultaneously (Krogstadt Ashpjell et al, 2010; Polder and Verick, 2004). For example, if the adoption of two ICT systems requires closing down a firm's network, it may decide to combine the planning and implementation of these systems out of efficiency considerations. In this sense, the simultaneous occurrence of new technologies can arise from both productivity advantages due to complementarities and/or cost advantages from joint adoption.

In this paper we therefore focus on the joint adoption of various new technologies, and document differences in the corresponding rates over countries, time, and industries. Firstly, we look at the rates of joint adoption. Higher rates of joint adoption are an indication of positive dependence between two decisions. But this is not necessarily the case, since higher penetration rates of single technologies also translate into higher rates of joint adoption. Therefore, in addition, we compare the rates of joint adoption to the corresponding marginal probabilities, in order to determine whether the joint rates are higher than expected when the concerning adoption decisions were independent. We introduce a term called the 'simultaneity ratio', which is the ratio of the joint probability to the product of the marginals. If this ratio is larger than 1, this is an indication for a positive dependence between two adoption decisions. We also present a test to determine if the number of cases where a particular ratio exceeds 1 is significant, exploiting the fact that we can calculate the ratio for different countries and industries.

After presenting the cross-country evidence we continue with a more advanced modelling of the adoption decisions. In this part we concentrate on the Netherlands. We consider the joint adoption of new technologies as a bivariate simultaneous discrete choice problem for firms. We model this by a simultaneous bivariate probit model, using insights from Lewbel (2007) and recent advances in estimating such a model by Simulated Maximum Likelihood put forward by Van Leeuwen and Mohnen (2012). In this model it is possible to identify to what extent two decisions affect each other simultaneously.

The plan of the paper is as follows. In section 2 we present the cross-country evidence with respect to the simultaneous adoption of innovation and e-business systems. Next, section 3 presents more advanced evidence on the joint dependence of these new technologies using Dutch micro-data. We discuss the theories that are broadly consistent with our empirical evidence, namely the theory with respect to complementarities, and that with respect to joint adjustment costs, in section 4. Section 5 concludes and sketches plans for extensions and future research.

2. Cross-country evidence on the simultaneous adoption of new technologies

2.1 The ESSNet project on "The linking of micro-data on IT"

The ESSNet project on "The linking of micro-data on IT" (ESSLimit) is a Eurostat funded project with 15 cooperating European NSIs aiming to provide new indicators and analyses with respect to the economic of impact ICT usage. The approach followed is the so-called Distributed Micro-Data (DMD) approach, as advocated in for example Bartelsman (2004). To overcome the impossibility of pooling microdata from different countries, in this approach the linking of various sources of micro-data is carried out by national statistical agencies 'onsite'. With information on the pertinent metadata, a common programming code is run that does the linking, calculates the indicators desired at all possible aggregation levels breakdowns and crossings, and likewise carries out a menu of different analyses. Aggregate indicators and analysis results are stored in output tables, which are collected on a secure web server and accessible by qualified researchers. For further analysis and benchmarking the individual countries' output tables (thus holding the aggregate results) can be pooled to larger cross-country datasets, which can be analysed directly or can be used as input for further regression analysis based on aggregates and possibly linked further to other datasets like EUKLEMS.

The data used by the project come (mainly) from the ICT survey (EC), the Community Innovation Survey (CIS), Production Surveys (PS), and Business Registers (BR). There are some differences over countries regarding mainly the sources of production variables and firm background variables from PS and BR. See Awano (2011) and Eurostat (2008) for a more detailed overview of the sources used.

The ESSLimit Project is a follow-up to the earlier ICT Impact project, see Eurostat (2008). One of the recommendations of this project, based on exploratory research in the Netherlands, United Kingdom, and Sweden, was to pursue the research on the linking of the EC survey with the CIS, both harmonized surveys giving an opportunity to explore and compare the link between ICT and innovation in a harmonized way using cross-country micro-data. In this context, the current paper should be seen as a first exploration of the ICT and innovation link based on the cross-country data, and an attempt to sketch more detailed analyses for the future with the available micro-data in hand.

Table 1 displays the overlaps between the ICT and innovation surveys. Both surveys are already based on samples, although in most countries larger firms are always covered. Thus, we should keep in mind that the joint sample is small relative to ICT and innovation survey sample, although the coverage can be seen to be well over 40% of the ICT survey sample on average. Moreover, because of the sampling strategy, the samples are likely to be biased towards larger firms. However, the ESSLimit database also includes weighted results, which we leave unexplored at this point.

2.2 Joint and marginal rates of adoption

One of the modules in the common code of the ESSLimit project calculates joint rates of adoption of technologies. These technologies cover a broad range of ICTs available from the EC (among which broadband, mobile internet, ERP, CRM, SCM, Automated Data Exchange et cetera) and innovation variables (product, process, organizational and marketing innovation, R&D, cooperation in innovative activities, et cetera), measured as binary variables. The module produces tables of the percentages of observations where technologies occur jointly, by country, industries and year. In principle, high rates of joint adoption are a sign of 'clustering', which is a first indication of complementarity and/or cost advantages of simultaneous adoption. In addition, for comparison to the joint rates, the marginal rates of adoption (i.e. the adoption rate of single technologies) can be taken from the STAT module, which computes averages of the pertinent variables.

Table 1: Number of observations for joint ICT and innovation survey sample.

country	sector	IS	EC	EC ∩ IS	% of EC	% of IS
FI	Elecom	194	204	98	0.48	0.51
FI	MServ	964	1931	287	0.15	0.30
FI	MexElec	1210	1190	540	0.45	0.45
FR	Elecom	847	367	176	0.48	0.21
FR	MServ	8585	4670	1374	0.29	0.16
FR	MexElec	5769	2535	1119	0.44	0.19
IE	Elecom	139	172	73	0.42	0.53
IE	MServ	1138	1871	240	0.13	0.21
IE	MexElec	714	1206	433	0.36	0.61
IT	Elecom	633	417	273	0.65	0.43
IT	MServ	8129	8173	3076	0.38	0.38
IT	MexElec	6197	5288	3190	0.60	0.51
NL	Elecom	303	297	129	0.43	0.43
NL	MServ	6433	3787	1580	0.42	0.25
NL	MexElec	2680	1853	960	0.52	0.36
NO	Elecom	323	115	99	0.86	0.31
NO	MServ	2623	2412	654	0.27	0.25
NO	MexElec	2000	803	590	0.73	0.30
SE	Elecom	381	119	102	0.86	0.27
SE	MServ	1576	1934	669	0.35	0.42
SE	MexElec	2104	823	749	0.91	0.36
UK	Elecom	753	206	63	0.31	0.08
UK	MServ	7710	2991	617	0.21	0.08
UK	MexElec	2904	1056	271	0.26	0.09

For reasons of exposition, we will make a selection of technologies, focussing on mobile internet connection (MOB), Enterprise Resource Planning (ERP), and Supply Chain Management (SCM) from the ICT survey, and product, process, and organizational innovation from the CIS. Moreover, we will restrict our attention to three main industries: ICT (electrical machinery plus post and communication services, 'Elecom'), market services (excluding ICT as defined before, 'MServ'), and manufacturing (excluding ICT as defined before, 'MexElec'), and to the year 2008. While in principle every crossing of the Boolean variables is available, we will focus here on the crossings of ICTs with the innovation variables since this is a relatively new area for which empirical evidence at the micro-level is scarce, especially in a cross-country setting (see Spiezia, 2011, for an exception).

Table 2a. Marginal and joint adoption rates of innovation types and mobile internet connection.

country	sector	mob × inpd	mob × inps	mob × mrkin	mob × orgin	inpd	inps	mrkin	orgin	mob
FI	Elecom	0.500	0.520	0.347		0.612	0.643	0.439		0.827
FR	Elecom	0.597	0.489	0.295	0.483	0.727	0.591	0.352	0.580	0.790
IE	Elecom	0.329	0.274	0.164	0.288	0.603	0.557	0.343	0.551	0.493
IT	Elecom	0.352	0.293	0.227	0.319	0.571	0.527	0.377	0.553	0.480
NL	Elecom	0.264	0.178	0.186	0.271	0.612	0.473	0.357	0.527	0.442
SE	Elecom	0.451	0.392	0.314	0.382	0.624	0.485	0.402	0.510	0.676
UK	Elecom	0.397	0.270		0.397	0.476	0.370		0.500	0.794
FI	MexElec	0.435	0.431	0.256		0.513	0.530	0.302		0.776
FR	MexElec	0.473	0.449	0.285	0.424	0.596	0.569	0.348	0.547	0.711
IE	MexElec	0.194	0.245	0.155	0.150	0.379	0.493	0.312	0.320	0.400
IT	MexElec	0.189	0.206	0.155	0.186	0.385	0.433	0.325	0.373	0.337
NL	MexElec	0.193	0.161	0.123	0.159	0.460	0.396	0.260	0.351	0.345
SE	MexElec	0.319	0.286	0.223	0.259	0.478	0.432	0.304	0.374	0.550
UK	MexElec	0.273	0.166		0.277	0.354	0.276		0.476	0.675
FI	MServ	0.352	0.373	0.185		0.387	0.418	0.206		0.819
FR	MServ	0.269	0.293	0.266	0.371	0.330	0.365	0.360	0.476	0.705
IE	MServ	0.196	0.221	0.171	0.175	0.287	0.375	0.318	0.307	0.517
IT	MServ	0.106	0.122	0.129	0.153	0.223	0.249	0.319	0.328	0.340
NL	MServ	0.109	0.111	0.128	0.148	0.223	0.224	0.254	0.289	0.409
SE	MServ	0.300	0.260	0.205	0.271	0.377	0.329	0.259	0.338	0.671
UK	MServ	0.217	0.130		0.287	0.266	0.191		0.411	0.763

Table 2b. Marginal and joint adoption rates of innovation types and IT systems (Enterprise Resource Planning).

country	sector	iterp × inpd	iterp × inps	iterp × mrkin	iterp × orgin	inpd	inps	mrkin	orgin	iterp
FI	Elecom	0.551	0.541	0.367		0.612	0.643	0.439		0.786
FR	Elecom	0.619	0.511	0.295	0.506	0.727	0.591	0.352	0.580	0.778
IE	Elecom	0.452	0.425	0.247	0.384	0.603	0.557	0.343	0.551	0.712
IT	Elecom	0.344	0.304	0.227	0.355	0.571	0.527	0.377	0.553	0.443
NL	Elecom	0.496	0.372	0.264	0.442	0.612	0.473	0.357	0.527	0.713
NO	Elecom	0.364	0.212	0.232	0.263	0.535	0.313	0.364	0.414	0.495
SE	Elecom	0.373	0.314	0.284	0.373	0.624	0.485	0.402	0.510	0.510
UK	Elecom	suppressed because of data issues								
FI	MexElec	0.413	0.420	0.246		0.513	0.530	0.302		0.722
FR	MexElec	0.466	0.441	0.271	0.424	0.596	0.569	0.348	0.547	0.722
IE	MexElec	0.171	0.187	0.120	0.148	0.379	0.493	0.312	0.320	0.309
IT	MexElec	0.186	0.200	0.147	0.177	0.385	0.433	0.325	0.373	0.296
NL	MexElec	0.372	0.310	0.202	0.291	0.460	0.396	0.260	0.351	0.679
NO	MexElec	0.244	0.183	0.186	0.180	0.402	0.290	0.303	0.295	0.500
SE	MexElec	0.362	0.322	0.220	0.298	0.478	0.432	0.304	0.374	0.606
UK	MexElec	suppressed because of data issues								
FI	MServ	0.230	0.220	0.122		0.387	0.418	0.206		0.526
FR	MServ	0.191	0.203	0.191	0.266	0.330	0.365	0.360	0.476	0.480
IE	MServ	0.092	0.142	0.117	0.133	0.287	0.375	0.318	0.307	0.333
IT	MServ	0.080	0.091	0.095	0.108	0.223	0.249	0.319	0.328	0.206
NL	MServ	0.111	0.108	0.128	0.135	0.223	0.224	0.254	0.289	0.379
NO	MServ	0.106	0.101	0.093	0.098	0.223	0.234	0.237	0.239	0.336
SE	MServ	0.203	0.179	0.158	0.181	0.377	0.329	0.259	0.338	0.425
UK	MServ	suppressed because of data issues								

Table 2c. Marginal and joint adoption rates of innovation types and IT systems (Supply Chain Management).

country	sector	sisc × inpd	sisc × inps	sisc × mrkin	sisc × orgin	inpd	inps	mrkin	orgin	sisc
FI	Elecom	0.337	0.337	0.235		0.612	0.643	0.439		0.510
FR	Elecom	0.341	0.318	0.182	0.301	0.727	0.591	0.352	0.580	0.438
IE	Elecom	0.137	0.151	0.096	0.137	0.603	0.557	0.343	0.551	0.247
IT	Elecom	0.234	0.220	0.161	0.249	0.571	0.527	0.377	0.553	0.377
NL	Elecom	0.271	0.233	0.171	0.264	0.612	0.473	0.357	0.527	0.372
NO	Elecom	0.192	0.121	0.141	0.131	0.535	0.313	0.364	0.414	0.343
SE	Elecom	0.255	0.216	0.206	0.216	0.624	0.485	0.402	0.510	0.389
UK	Elecom	0.206	0.175		0.190	0.476	0.370		0.500	0.286
FI	MexElec	0.219	0.209	0.146		0.513	0.530	0.302		0.367
FR	MexElec	0.250	0.233	0.146	0.220	0.596	0.569	0.348	0.547	0.354
IE	MexElec	0.055	0.060	0.046	0.058	0.379	0.493	0.312	0.320	0.104
IT	MexElec	0.142	0.164	0.121	0.146	0.385	0.433	0.325	0.373	0.291
NL	MexElec	0.154	0.135	0.089	0.135	0.460	0.396	0.260	0.351	0.267
NO	MexElec	0.097	0.080	0.085	0.075	0.402	0.290	0.303	0.295	0.224
SE	MexElec	0.211	0.199	0.128	0.195	0.478	0.432	0.304	0.374	0.351
UK	MexElec	0.103	0.077		0.103	0.354	0.276		0.476	0.214
FI	MServ	0.167	0.181	0.084		0.387	0.418	0.206		0.436
FR	MServ	0.103	0.117	0.108	0.138	0.330	0.365	0.360	0.476	0.254
IE	MServ	0.042	0.063	0.046	0.054	0.287	0.375	0.318	0.307	0.108
IT	MServ	0.081	0.091	0.112	0.119	0.223	0.249	0.319	0.328	0.265
NL	MServ	0.072	0.067	0.077	0.091	0.223	0.224	0.254	0.289	0.231
NO	MServ	0.073	0.080	0.078	0.087	0.223	0.234	0.237	0.239	0.275
SE	MServ	0.139	0.136	0.102	0.127	0.377	0.329	0.259	0.338	0.319
UK	MServ	0.057	0.029		0.076	0.266	0.191		0.411	0.204

Table 2a to 2c show the joint and marginal rates of adoption for the crossing of the ICTs with innovations. We see strong variation within countries (over industries) and within industries (over countries). It is difficult, however, to compare these numbers and make inferences about a positive dependence between the two. In general, if the combination of two types has a high joint adoption rate, the individual types also have a higher marginal rate of adoption. This makes sense, since if it is beneficial to adopt technologies jointly, this will also increase the marginal rates. But if two technologies simply happen to be well diffused in a certain country and/or industry, joint adoption would still be high regardless of any further relation between them.

We therefore compare the joint adoption rates to the marginal rates of adoption, by introducing a quantity we label the 'simultaneity ratio' (R),

$$R(\mathrm{A,B}) = \Pr(\mathrm{A} \cap \mathrm{B})/(\Pr(\mathrm{A}) \times \Pr(\mathrm{B})),$$

where A and B are events of adoption. Thus, R is the ratio of the joint probability to the product of the marginal probabilities of A and B. We can interpret the figures in table 2a to 2c as sample estimates of the pertaining probabilities. The denominator $\Pr(\mathrm{A})\times\Pr(\mathrm{B})$ is the counterfactual probability of joint occurrence, if A and B were independent. Thus, if $\Pr(\mathrm{A} \cap \mathrm{B})$ is larger than $\Pr(\mathrm{A})\times\Pr(\mathrm{B})$, and hence if $R > 1$, this means that the observed probability of joint occurrence is larger than what would be expected if the two events were independent. In this case, we may conclude that the two events have a tendency to occur jointly.[1]

A word of caution is still in place if one wants to compare R over countries, because if it is higher in a particular country compared to another, it does not necessarily say that there is a stronger positive dependency between the concerning two technologies. This is because a stronger positive dependency leads to higher joint adoption, but also to higher marginal adoption rates. In the limit, two technologies may be fully diffused, and hence always occur together, resulting in $R = 1$. Hence, a higher R is not per definition a sign of stronger complementarities[2].

When R is higher than 1, it can be seen as an indication that adoption of two technologies is interrelated. We can distinguish three cases:

1. R is significantly lower than 1: joint adoption of two technologies is lower than expected, which could be associated with negative association between the technologies;
2. R is close to 1:

[1] Alternatively, R can be seen as the ratio of the conditional sample probability of A (B) given B (A), to the marginal sample probability of A (B), i.e. $R = \Pr(\mathrm{A} \mid \mathrm{B})/\Pr(\mathrm{A}) = \Pr(\mathrm{B} \mid \mathrm{A})/\Pr(\mathrm{B})$. In this interpretation, R is the factor by which the probability of an event A increases given that the event B also occurs. In other words, it gives the amount of information about A in knowing about event B. Clearly, if there is a strong positive dependency, $R > 1$.

[2] It may be more sensible to look at a Pearson correlation for this purpose, but at this point these are unavailable.

a. if the marginal adoption rates are high, both technologies are well diffused, and we can make no inference about whether there is a dependence among the two from *R*;

b. if the marginal adoption rate are relatively low, an *R* around 1 means that there is no strong indication that the adoption of two technologies are either positively or negatively interdependent;

3. *R* is well above 1: the joint adoption of two technologies is higher than expected, indicating a positive dependence among the individual adoption decisions.

From the marginal rates in table 2a to 2c we know that there is a substantial number of non-adopters for the technologies considered, so case 2.a. is not relevant in our case. Thus, an *R* close to 1 is a sign of low interdependency between the adoption decisions, and not of high individual diffusion rates. Moreover, it makes sense to compare conclusions about *R*, rather *R* itself, over countries/industries.

Figures 1a to 1c plot the simultaneity ratio *R* for various ICTs and innovations in our dataset for all countries and the three industries under consideration. Although there are some exceptions, we see that there is an overall tendency of combining technologies that is higher than what would be expected from the marginal rates of adoption. By way of example, we look at the pattern of SCM and product and process innovation (figure 1c). Again there are interesting differences over countries, and over industries here. In the UK, for instance, the figures point at a substantial dependency between SCM and product and process innovation in Elecom and MexElec, but not in MServ. There even seems to be a negative relation between SCM and process innovation in the UK in MServ. In other countries, dependency between SCM and both technological innovations in MServ is quite strong, except in Finland. For example, in Ireland there is a strong indication of dependency between process innovation and SCM in MServ.

Figure 1a: Simultaneity Ratio (*R*) mobile internet with innovation types by year.

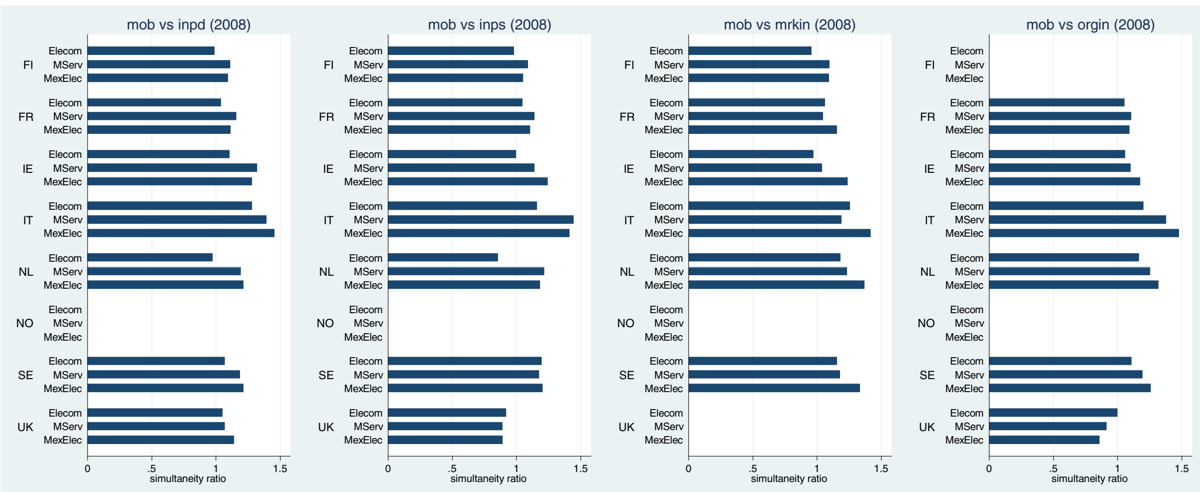
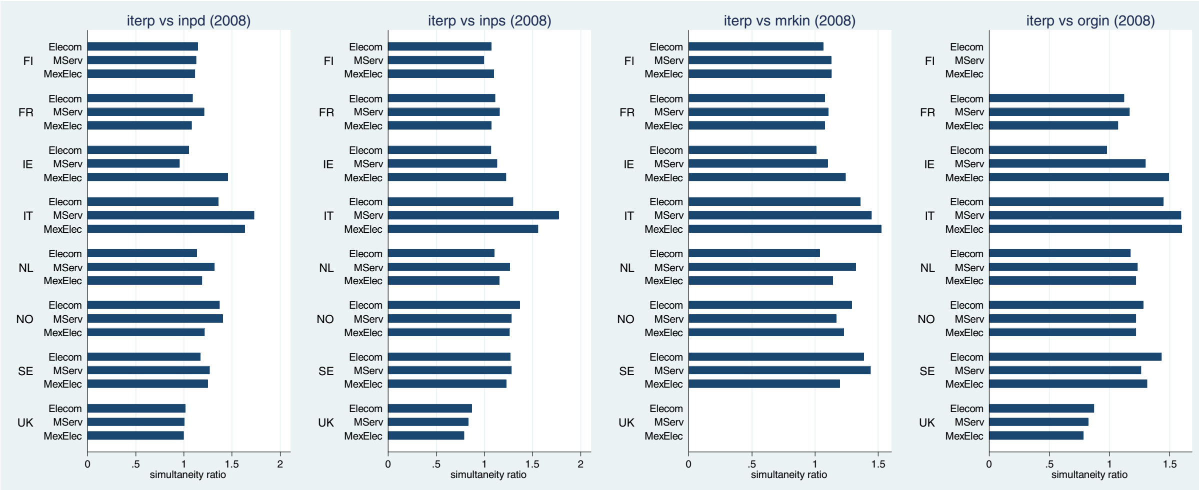


Figure 1b: Simultaneity Ratio (R) Enterprise Resource Planning with innovation types by year



Nb. UK figures to be ignored due to data issues.

Figure 1c: Simultaneity Ratio (R) Supply Chain Management systems with innovation types by year.

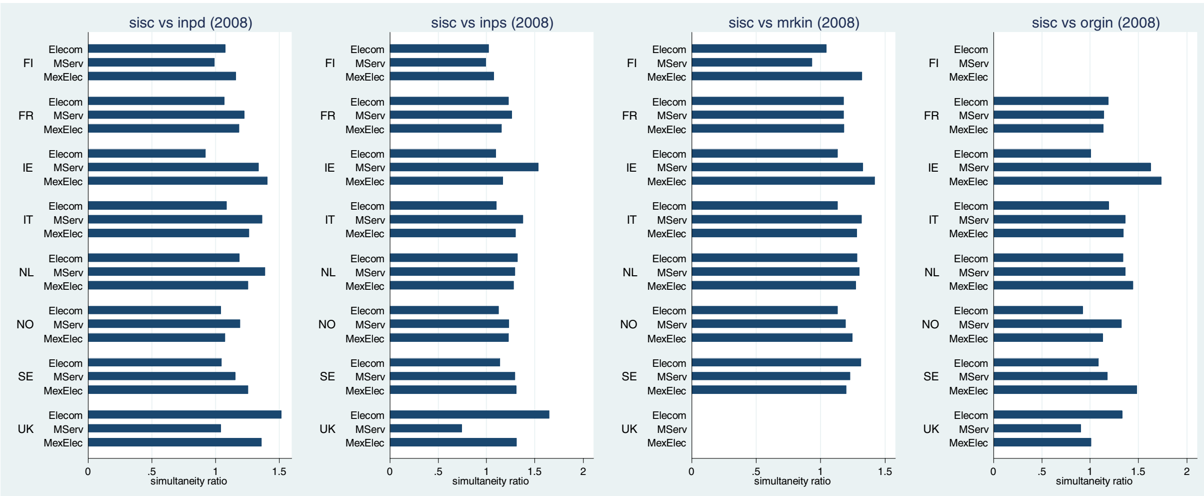


Table 3 shows the averages of R over countries and industries (for 2008, and when available 2004 and 2006), which are well over 1. We also test whether the count of the number of cases where $R > 1$ is significantly higher than random (i.e. 50%). This is the case for all combinations when maintaining a significance level of 5%.

Thus, from the overall descriptive evidence, we conclude that there seems to be a tendency of positive dependence between the adoption of all of the technologies considered, with some interesting variation over countries and industries. It remains to be investigated what explains these cross-country and cross-industry differences. In section 4, however, we highlight two explanations for the existence of a positive dependence between two technologies, being 1. mutual complementarities in the product process and 2. possible cost advantages to simultaneous adoption. An interesting question is whether the results in differing patterns of joint adoption can be explained by differences in the degree of complementarity and/or variations in the adjustment cost structures within and between countries and/or industries, and also the possible interplay between these mechanisms. A next step would be to identify differences between countries and industries with respect to the magnitude of complementarities and adjustment costs, and compare those to the observed adoption rates.

Table 3: Sign test for the simultaneity ratio (Pr(R > 1) > 50%))

combination	mean	std. dev.	*p*-value sign test	*N*
mob vs inpd	1.131	0.210	0.000	48
mob vs inps	1.076	0.204	0.003	48
mob vs orgin	1.069	0.214	0.040	33
mob vs mrkin	1.226	0.194	0.000	27
iterp vs inpd	1.176	0.177	0.000	42
iterp vs inps	1.140	0.180	0.000	42
iterp vs orgin	1.159	0.227	0.049	30
iterp vs mrkin	1.210	0.138	0.000	27
sisc vs inpd	1.164	0.153	0.000	30
sisc vs inps	1.186	0.180	0.000	30
sisc vs orgin	1.252	0.218	0.000	21
sisc vs mrkin	1.221	0.115	0.000	24

Table note: complementarity factor = Pr(A ∩ B)/(Pr(A)×Pr(B)).
Pr(A ∩ B): the observed probability of joint occurrence of A and B.
Pr(A)×Pr(B): the theoretical probability of joint occurrence if A and B are independent events.

3. Modelling simultaneous adoption decision and results for the Netherlands

A positive dependence between two choices results in clustering, but as stated in the previous section vice versa this clustering is only indicative for this positive dependence. That is to say, clustering does not imply positive dependence. Indeed, there may be other factors explaining why both occur. A more rigorous approach models the probabilities of two events as two jointly dependent stochastic variables, while controlling for potential other factors that might affect these probabilities. That is, if y_1 and y_2 are the two events of interest, and $y_i = 1$ indicates that the event occurred,

(1a) $\Pr(y_1 = 1) = \alpha_{12} y_2 + X_1'\beta + \varepsilon_1$

(1b) $\Pr(y_2 = 1) = \alpha_{21} y_1 + X_2'\beta + \varepsilon_2$

If we assume that ε_1 and ε_2 are jointly normally distributed, the system (1a) and (1b) is a multivariate probit model. However, this model deviates from the standard multivariate probit model in that the pertinent choices are simultaneously dependent. This is the model described by Lewbel (2007) and elaborated upon by Van Leeuwen and Mohnen (2012). It can be estimated by Simulated Maximum Likelihood as in the case of multivariate probits (see Cappellari and Jenkins, 2003), but for each combination of choices, the likelihood is different and the integration bounds need to be adjusted. (For the case of two choices as considered here, there are four possible combinations: (0,0), (1,0), (0,1), (1,1).) If we assume that there is no order between the adoption decision y_1 and y_2, only the sum of α_{12} and α_{21} is identified in this model, but it can shown that positive dependency between choices results in $\alpha_{12} + \alpha_{21} > 0$. See Van Leeuwen and Mohnen (2012) and Polder et al. (2012) for a more extensive account on the estimation methodology.

Table 4 gives the results for the Netherlands for the estimation of the system of equations (1a)-(1b) along these lines. In this case we have looked at the joint adoption of (either) ERP, CRM and SCM IT systems with (either) product, process and organizational innovation. We use several dummy variables by way of (exogenous) control variables: a dummy for being part of an enterprise group, for receiving funding for innovation, for being active on a foreign market (exporter), for cooperating on innovative activities, for being a (structural) R&D performer, and for economic activity (four main categories: Elecom, MexElec, MServ, and OtherG(oods, used as a reference category)). In addition, we control for overall ICT intensity in the firm (percentage of broadband usage, defined as the percentage of internet users times a dummy for having broadband, see Eurostat, 2008), and size (number of workers from the business register). To save space we only report the estimates of the α's, which are the sums of α_{12} and α_{21} in each bivariate model.

We find a positive joint dependence of all IT systems with product innovation. Thus, for each IT system considered the probability of adoption is increased with the simultaneous adoption of a product innovation, and vice versa. Similarly, we find a positive dependence for CRM and SCM with organizational innovation, but not for ERP and organizational innovation. The latter may be surprising, but in 2008 it could be the case that the use of ERP was already well established and corresponding changes in the organizations had already been made. On the other hand, CRM and SCM are somewhat newer and successful adoption of these system is found to depend on the existence of an ERP system (see Aral et al. 2006). Thus, CRM and SCM may go hand in hand with new organizational changes. Finally, we find a positive mutual dependence among process innovation and SCM, but no mutual dependence among process innovation and CRM. The relation with ERP is even negative. Again, ERP may have been adopted at an earlier stage together with pertinent changes in the production process. Given that these changes are rather disruptive, firms having introduced a process innovation in recent times may be less keen to adopt new processes when ERP is already in place.

In the future we aim to extend the sample to other countries within the ESSLimit consortium, to be able to compare the relation between different IT systems and innovation over countries. This should also put our interpretation of the results into an international perspective.

Table 4: Estimates of cross-dependence between IT systems and innovations for the Netherlands (2008).

		product innovation		process innovation		organizational innovation	
		α	se	α	se	α	se
ICT	ERP	0.070**	0.032	-0.128***	0.035	0.021	0.032
	CRM	0.176***	0.032	-0.026	0.031	0.112***	0.031
	SCM	0.197***	0.046	0.098***	0.035	0.306***	0.038
N	2175						
draws	50						

4. Two explanations consistent with the empirical evidence of joint dependence

In sections 2 and 3 we presented empirical evidence that shows a general tendency of firms combining the adoption of new technologies. In this section we briefly discuss two possible theoretical explanations for why firms may decide to adopt two (or more) technologies jointly.

4.1 Complementarities in the production function

Two technologies are complementary if the gains to the adoption of both technologies are mutually positively affected. This may be caused by certain synergetic effects. Thus, for example the implementation of a new IT system may be more advantageous if a training program is also setup, or complementary organizational practices are put into place, while vice versa the training program as well as the new organizational practices may be more effective if the new IT system is introduced. If managers recognize such complementarities, this will result in the joint adoption of complementary practices and the observation of a positive dependence among such practices.

The idea of complementarities, or that firms will adopt strategies that 'fit' together, is due to the seminal work by Milgrom and Roberts (1990, 1995). Empirical work that has confirmed the importance of this notion has usually focussed on the complementarity between IT and various work practices and management methods, see among others Bloom et al. (2012), Black and Lynch (2004), and Ichinowski et al. (1997). The finding that organizational practices and IT are complementary is also prominent in the work by Brynjolfsson and others, see Brynjolfsson and Saunders, 2010, and the references therein.

4.2 Adjustment cost advantages of simultaneous adjustment

Adjustments are costly for a firm. They disrupt the production process in many possible ways. For example, the physical implementation of new technologies could require closing down a production line for a given time. The introduction of improvements in the production process or the adoption of new IT systems requires workers to get used to operate these new technologies, or it may require them to be (re)trained. The structure of these so-called adjustment costs determines the dynamics of how a firm reacts to economic shocks (Hamermesh and Pfann, 1996). In particular, if these costs are marginally increasing, firms will spread adjustment over time, but if costs are marginally decreasing (as in the case of a fixed cost component), firms have the incentive to concentrate adjustment in short periods of time. Moreover, if adjustment costs have a joint component, the dynamics of a firm's decision variables, will be interrelated (Shapiro, 1986). For example, if workers need to be retrained to adapt to a new technology, it may be cost efficient to adopt several new technologies at once to combine and concentrate the training efforts.

When there are fixed or otherwise non-convex adjustment costs, firms alternate periods of heavy adjustment with inaction (Hamermesh, 1989). That is, the decision to adjust is broken down into a decision on the extensive and intensive margin. Moreover, if adjustment costs are partly fixed (or otherwise non-convex) and there is a common component to these costs, the decision on the extensive margin becomes interrelated (Asphjell et al, 2010, Polder and Verick, 2004). Thus, in taking the decision whether to adjust a certain variable or not, a firm will take into account possible cost advantages to the adjustment of other variables.

The adjustment cost literature is focussed mainly on decisions on investment and labour, but the reasoning with respect to making the yes/no decision to adjust may well apply to the adoption of new IT systems and innovation as well. Thus, besides complementarities discussed in the previous subsection, cost advantages to the simultaneous adoption of several technologies could also explain the observed positive dependence between these adoptions.

To our knowledge, the topic of interrelated adjustment costs has not been investigated in the context of the adoption decision with respect to new technologies. Thus, in our view, this makes for an interesting line of future research, especially to answer the question how these adjustment costs may interact with the complementarities in the production process described above.

5. Conclusion

5.1. Summary

The paper takes a first look at the module with respect to the joint adoption of technologies in the cross-country dataset under construction in the ESSLimit project. Using this dataset based on linked micro-data from 15 European countries, we document empirical evidence on the individual and joint adoption of different types of innovation (product, process, organizational and marketing) and different types of Information and Communication Technologies (ICTs), varying from mobile internet connection to IT systems as Enterprise Resource Planning, Supply Chain Management and Customer Relation Management (ERP, SCM, CRM) software suites. We identify differences between countries and sectors, but overall there is evidence of a substantial amount of joint adoption of, and therefore a positive dependence between, different new technologies. We present a more rigorous analysis of joint adoption using micro-data from the Netherlands. Using a novel methodological approach we estimate bivariate models of adoption, where the decision with respect to one adoption is affected by the decision with respect to another adoption. We find significant positive dependence between the adoption of IT systems and product and organizational innovation, but less so in the case of process innovation. We argued that the finding of positive dependence between adoption decisions is consistent with at least two theories about firm investment decisions: complementarities in firm strategies and advantages in adjustment costs of simultaneous adjustment.

5.2. Suggestions for future research

– Assessing the role of interrelated adjustment costs and complementarities

We discussed two theories explaining possible joint adoptions of new technologies, namely complementarities and (interrelated) adjustment costs. It is a challenge to investigate whether differences in the magnitude of these cost or profit advantages between countries and industries can help explain the adoption patterns. Moreover, an even bigger challenge is the development and estimation of a structural model including complementarities and interrelated adjustment that will help to assess the relative importance of these mechanisms for explaining the adoption patterns observed. Such a model should enrich the insights from Asphjell et al. (2010) with those of Milgrom and Roberts (1995).

– Assessing complementarities by estimating augmented production function

Complementarities reveal themselves in two ways: in higher rates of joint adoption, and in higher productivity for firms who do joint adoption (see also Brynjolfsson and Saunders, 2010). In addition to the cross-country evidence on joint adoption we can therefore also take a look at increased productivity after joint adoption, see e.g. Polder et al. (2010). This approach uses dummies for different adoption profiles in an augmented production function.

Consider the Cobb-Douglas production function given by:

$$VA_t = A_t IT_t^{\alpha_1} K_t^{\alpha_2} L_t^{\alpha_3} \Leftrightarrow \log(VA_t / L_t) = a_t + \alpha_1 it_t + \alpha_2 k_t + (\alpha_3 - 1) l_t$$

where VA_t is value added, IT_t is the stock of IT capital, K_t is the (non-IT) capital stock, and L_t is employment. The term A_t reflects differences in firm output that are not related to differences in inputs, and is usually referred to as total factor productivity (TFP). If we distinguish between three types of adoption there are 8 (= 2^3) innovation profiles $d_{jt} j = 1,...,8$, $i_k \in (0,1)$.

To investigate whether the adoption profiles explain productivity differences, we may parameterize a_t by innovation profile dummies d_{jt},

$$a_t = \sum_j \gamma_j d_{jt} + \varepsilon_t \, .$$

By comparing coefficients on each of the innovation profiles, one can test for complementarities (see e.g. Carree et al. 2010, Kodde and Palm, 1984)). The current code run included these regressions but it seems that at this stage some fine tuning is needed to get to comparable results over countries.

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