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Investigating the effects of ICT on innovation and performance of European hospitals: an exploratory study

Spyros Arvanitis[1] · **Euripidis N. Loukis**[2]

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Abstract Hospitals are making big investments in various types of ICT, so it is important to investigate their effects on innovation and performance. This paper presents an empirical study in this direction, based on data for 743 hospitals from 18 European countries. We specified and estimated econometrically five equations: one for product innovation, one for process innovation and three equations for the three different dimensions of (ICT-enabled) hospital performance. All five equations included various ICT-related variables reflecting ICT infrastructure and a series of important ICT applications, some of them hospital-specific, and some others of general business use, and also ICT personnel (viewed as a kind of 'soft' ICT investment), while the performance equations also included the two innovation measures.

Keywords Hospitals · Innovation · Performance · ICT use

JEL Classification O31

✉ Spyros Arvanitis
arvanitis@kof.ethz.ch

Euripidis N. Loukis
eloukis@aegean.gr

[1] KOF Swiss Economic Institute, ETH Zurich, 8092 Zurich, Switzerland

[2] Department of Information and Communication Systems Engineering, University of the Aegean, 83200 Karlovassi/Samos, Greece

Introduction

This study investigates the impact of the use of modern information and communication technologies (ICTs) on innovation and performance of European hospitals. Hospitals began investing in health ICTs in the 1960s, and since then have made big investments for the development of various types of ICT applications. ICTs were first used to support auxiliary functions, such as financial services; in a later phase, ICTs were utilized to manage pharmacy, laboratory and radiology service lines, thus to monitor and support clinical activities.[1] The respective ICT applications facilitated important services, such as drug interaction controls, laboratory quality controls and documentation of patient's radiology records. These systems were already quite widespread among USA hospitals by 2000 [34]. Two further important technologies that were subsequently developed were electronic medical record (EMR) systems and computerized providers order entry (CPOE) systems. The development of EMR has greatly expanded the automation of clinical services. These systems integrate information from pharmacy, radiology and laboratory in a way that allows physicians to directly access this information and have a complete and integrated picture of a patient. The technology of CPOE is aiming at reducing communication errors and serving as a platform for treatment guideline automation; it enables the electronic entry of physicians' orders for examinations and treatment of patients, which are communicated over a computer network to the medical staff of the pharmacy, laboratory and radiology departments responsible for fulfilling these orders, and finally the results are communicated back to the physicians. It is only during the past decade that the latter

[1] We draw here on McCullough [34] and Lee et al. [31].

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technology has begun to diffuse widely. The combined use of these two technologies "should standardize care and reduce errors, thus enhancing both clinical quality and productivity" [31]. These two technologies have been investigated by a series of USA studies with respect to the determinants of their diffusion (e.g., [18, 34]) as well as their impact on clinical quality and productivity (see the literature review in "Conceptual background and related empirical literature").

A previous study examined ICT adoption, particularly adoption of EMR, in seven countries (the USA, Canada, Australia and New Zealand, besides three European countries—Germany, the Netherlands and the UK) and found that many of them have achieved high levels of ambulatory EMR adoption, but lagged with respect to hospital adoption of this technology (see [26]). Adoption rates in hospitals were less than 10 % until 2005 with not large differences among these countries. However, the authors mentioned that they "found almost no high-quality, reliable data on Electronic Health Records in acute care settings from any of seven countries" (p. 850). Since then, the data situation in Europe has improved. The data used in this study show that the percentage of hospitals in 18 European countries using medical records management systems and CPOE amounted to 67.4 and 33.7 %, respectively, in 2005.[2] Therefore, ICT endowment has now reached a level in Europe that allows investigation of the possible effects of ICT use, not only on the performance of European hospitals (a topic that is particularly examined in USA studies), but also on hospital innovation, which is presumably an important determinant of hospital performance.

This study intends to contribute to the literature in three ways. First, it is, to our knowledge, the first comprehensive study of this kind for European hospitals. Second, it analyzes the effects of various types of ICT on innovation and (ICT-enabled) economic performance of hospitals in an integrated framework. Third, it is based on relatively detailed information on ICT infrastructure and specific ICT applications, both health-specific and general, and also on ICT personnel, examining and comparing their effects on innovation and economic performance.

However, it should be mentioned that the conclusions drawn from our study might be strongly associated with the European context, and may not necessarily hold for other regions.

The paper is structured as follows. "Conceptual background and related empirical literature" deals with the conceptual background and related literature, "Data" presents the data and "Model specification" the model specification. In "Results" the results of the econometric analysis are presented, while "Summary and conclusions" concludes the paper.

Conceptual background and related empirical literature

Innovation in the health sector

The existing literature on innovation activities in hospitals is scarce. There are at least two reasons for this: first, conceptual difficulties in applying the standard innovation definition, which has been primarily developed for technological novelties in manufacturing, to the health sector; and second, the lack of innovation data for hospitals. Djellal and Gallouj [20] state in their survey article that existing studies on hospital innovation are case studies, but there are no comprehensive studies based on larger samples of hospitals.[3] An usable concept of hospital innovation that remains quite close to the standard innovation concept was developed in a project financed by the European Union, and then applied in case studies from five countries (Ireland, the Netherlands, Spain, Sweden and the UK) [16]. The innovation concept used in the present study (and also in the e-business survey 2006; see "Data") covers—in analogy to the concept of the Community Innovation Surveys—new products, services and processes that are either new for a certain hospital or/and new for hospitals in a certain country or even worldwide.

To our knowledge, the only study that investigates explicitly the innovation performance of hospitals is the study of Salge [43]. It is based on data for 153 public hospitals in the UK. The main findings were that differences as to innovation performance among the hospitals can be explained by firm size, the availability of resources and different "strategical aspirations" of hospital management. We know of no study that deals with the effects of ICT on hospital innovation, which is the main topic of this paper.

ICT and innovation[4]

Kleis et al. [27] argue that the use of ICT contributes to firms' innovation activities through three main channels. The first channel goes through the improvement of the

[2] For a descriptive study on the diffusion of some ICT uses in European hospitals that is based on the same data as this study see Mikalef and Batenburg [37]; see also the European Commission [22]. For the perspectives of eHealth infrastructures in European countries see Stroetmann et al. [45].

[3] The same authors provide an analytical concept of innovation in hospitals, which is too abstract to be easily operationalized in empirical studies [19]. For a conceptual approach specific to "innovation in healthcare" see Thakur et al. [48].

[4] This section is based on Arvanitis et al. [3], where a brief review of empirical literature can also be found.

management of the knowledge used in the innovation process. This knowledge might be internally created or externally acquired. Information technology 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. This is particularly the case for external information, which is critical for successful innovation [28, 30].

Second, ICT enables a more efficient cooperation in innovation with external partners. The creation of new knowledge through collaboration with other firms has become more and more important in the last 20 years [21]. Information technology facilitates the exchange of information with external partners that are located far away from the focal firm.

Third, ICT contributes directly to the innovation production in several ways. Kleis et al. [27] 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 (e.g., customer relationship management, CRM) that enable a firm to analyze customers' communication and transaction data, and identify needs that can be covered by new products or significant modifications of existing products. Further, information technology 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. Finally, ICT helps integrate design and 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.

Furthermore, ICT can also directly drive ICT-based innovations in firms' processes, products and services, and even business models [11, 12, 47]. It can transform existing business processes and enable new products and services, and also existing products' and services' variety and personalization, which were not operationally and economically feasible before, without ICT.

We assume that these general notions about the possible relationship between innovation and ICT can be also applied to the health sector. In sum, we expect a positive impact of ICT through these three channels on innovation performance.

ICT and hospital performance

Existing empirical literature on the influence of ICT on hospital performance is more extensive than that for the effect of ICT on hospital innovation, but it refers almost exclusively to USA hospitals and the situation in the USA health sector (see, e.g., [13] for a survey of this literature).[5]

The group of USA studies, which we consider here as a relevant reference, examined the impact of ICT use in hospitals on the quality of healthcare [1, 35], certain patient outcomes [36], hospital productivity [31], hospital cost efficiency [40], hospital operating costs [10] and the efficiency of the utilization of clinicians [6].

On the whole, as Buntin et al. [13] also wrote in their survey, the existing literature shows predominantly positive results of ICT use on hospital performance. These effects are mostly small and, for many authors, the modest magnitude of these effects indicates that even if ICT in hospitals contains a great potential, the efficient utilization of it takes time. A comparison of the outcomes of most studies is complicated by the fact that quite varying measures of ICT, measures of hospital performance and differing modeling approaches are used.

We know only two studies that deal with the effects of ICT use in European hospitals. Stroetmann et al. [46] investigated the economic impact of ten European eHealth applications by conducting a cost-benefit analysis of the ten ICT applications in different European countries. All ten cases showed a positive economic impact. The average time needed for total benefits to exceed total costs was 5 years. Further, a European Commission report [22] contains a short descriptive analysis of the results of the 2006 survey for hospitals, where the data for this study also come from.

Research hypotheses

Based on the previous section we can formulate two research hypotheses concerning the impact of ICT on process and product innovation in hospitals, respectively. ICT can lead to significant innovations in the processes of the main hospital's functions, such as patient care, administration, clinics, pharmacies, laboratories, etc. In particular, it can drive improvements, simplifications and standardization of them by enabling the automatic execution of some of their tasks, transformations of some others or changes of their sequence (e.g., allowing previously serial tasks to be executed in parallel), or even eliminating some tasks (e.g., making some check tasks unnecessary) [11]. Also, some healthcare-specific applications (e.g., CPOE, medical images archiving and transmission) and also some general ones (e.g., ERP) can improve integration and coordination between different departments (e.g., the former between

[5] We refrain here from surveying empirical literature that deals with the influence of technology and innovation in general on productivity in health care (see, e.g., [7, 32, 44]).

clinics and laboratories, or the latter between financial departments and clinics), lead to the establishment of new horizontal processes, and introduce new work organization and practices [31]. Furthermore, such applications will result in the collection and integration of large quantities of data, the analysis of which might reveal significant weaknesses and problems of existing processes (e.g., through the calculation of appropriate analytics), resulting finally in innovative changes in them. Also, the development of ICT systems which are interoperable with the ones of cooperating organizations (e.g., other hospitals or health centers, suppliers, etc.), can lead to significant innovations in the processes of cooperation and transaction with them [33]. For the above reasons we expect that ICT will have a positive impact on process innovation in hospitals. So our first research hypothesis is:

Hypothesis 1 ICT has a positive impact on process innovation in hospitals.

Furthermore, according to innovation literature, the exchange and combination of data and knowledge between various functional domains of an organization, and also with other organizations (from the same sector and from other sectors), are of critical importance for product innovation (see, e.g., [14, 39, 49]). So the exchange of data between different functions and departments of a hospital that are enabled by various healthcare-specific applications (e.g., CPOE, medical images archiving and transmission) and also general ones (e.g., ERP), is expected to have a positive impact on product innovation, as it will promote the exchange of information and knowledge and the generation of innovative ideas concerning the introduction of various pharmaceutical, therapeutic or biomedical novelties, and also will enable the cost-efficient implementation of them. Also, the development of ICT systems that are interoperable with the ones of cooperating organizations, such as other hospitals or health centers, suppliers, etc., will facilitate the exchange of data and knowledge, so it will be another important source of such innovative ideas, and a strong facilitator of their implementation. The use of CRM systems allows collecting valuable data about patients' needs, which can also lead to important product innovations. In general, ICT can enable the development of new products, and also higher levels of variety and personalization of existing ones, which would not be operationally and economically feasible without ICT. For the above reasons we expect that ICT will have a positive impact on product innovation in hospitals. So our second research hypothesis is:

Hypothesis 2 ICT has a positive impact on product innovation in hospitals.

The relationship between innovation and firm performance is a topic that has been extensively researched in economics (see [17] for a seminal paper with a prominent influence on subsequent studies; [38] for a survey of the respective empirical literature). Most studies find a positive effect of innovation on firm performance, which is usually measured by some productivity measure (labor productivity or total factor productivity). Productivity measures based on value added (revenues minus intermediate inputs) of production are not the appropriate measures of hospital performance. Usually, measures such as the "quality of patient care" (based, e.g., on indicators of patient mortality, medical complication cases and readmission rates) or the "efficiency of hospital processes" (based, e.g., on the "number of patient days in hospital") are used for this purpose. In analogy to existing empirical literature on the relationship between innovation and performance in general, we assume that product and/or process innovation in the sense discussed in "Innovation in the health sector" would affect positively measures of hospital performance. In particular we expect that product innovation (e.g., pharmaceutical and biomedical and technical novelties, novel surgical and therapeutic procedures, etc.) will lead to higher quality of patient care and higher revenue. Also, we expect that process innovation (e.g., better processes of horizontal integration of departments) will lead to improvements in the quality of patient care and the efficiency of the processes, and through them to revenue increase.

In this study we do not have data on performance measures but only information on the performance impact of ICT. Thus, our hypotheses with respect to performance refer to the possible influence of innovation as a mediating factor that could reinforce the impact of ICT. The idea of complementarity between innovation and ICT as to economic performance has been investigated in many empirical studies and has been mostly confirmed (e.g., [25] for German and Dutch service firms; [23] for Australian firms). For Italian manufacturing firms the empirical evidence is mixed: Hall et al. [24] found no complementarity between ICT and R&D as to productivity; Biagi and Parisi [9] found complementarity between ICT and particularly organizational innovations with respect to Italian manufacturing firms. As a consequence, the respective hypothesis is:

Hypothesis 3 Innovation has a positive impact on ICT-enabled hospital performance.

Data

The data come from the e-business survey 2006 of the European Union. The survey covered all members of the European Union at that time (EU-25) plus Norway and Turkey, and ten sectors, among them healthcare (hospitals). It was based on a questionnaire that contained in ten modules questions on ICT infrastructure, ICT expenditure,

e-collaboration, e-standards and interoperability issues, general characteristics of the surveyed entities, such as number of employees, employee formal qualification, year of foundation, as well as measures of innovation and economic performance. Interviews were carried out in March and April 2006, using computer-aided telephone interview (CATI) technology. The decision-maker in the entity targeted by the survey was normally the person responsible for ICT within the hospital/enterprise. Alternatively, particularly in small hospitals, the managing director was interviewed. The survey included only hospitals/enterprises that used computers. The sample drawn was a random sample of hospitals from the respective sector population in each of the countries considered, with the objective of fulfilling minimum strata with respect to size class per country-sector cell. 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. For this study we used the subset for hospitals that contained information for 18 countries (see Table 1).[6] From the originally 932 observations (about 5 % of all European hospitals) we excluded hospitals with fewer than ten employees in order to allow for some minimum size that implies a wider spectrum of activities (see Table 1 for the composition of the dataset). Due to missing values for some variables, the dataset that was used for the econometric estimates contained 678 observations. Table 6 in the appendix contains some descriptive statistics for the observations used in the empirical work, while Table 7 shows the correlations among model variables. Table 2 presents information on the frequency of various ICT applications used in European hospitals. Seven of them are hospital-specific and refer to administrative, medical and patient-specific services.[7]

Table 1 European hospitals: composition of the dataset by country, size class, specialization and ownership status

	N	Percentage
Country		
Belgium	20	2.7
Czech Republic	49	6.6
Germany	96	12.9
Greece	16	2.2
Spain	30	4.0
France	76	10.2
Italy	36	4.9
Latvia	48	6.5
Lithuania	37	5.0
Hungary	47	6.3
The Netherlands	6	0.8
Poland	90	12.1
Portugal	46	6.2
Finland	32	4.3
Sweden	10	1.4
United Kingdom	31	4.2
Turkey	64	8.6
Norway	9	1.2
Firm size (number of employees)		
10–49 employees	120	16.2
50–99 employees	91	12.3
100–199 employees	138	18.6
200–499 employees	183	24.5
500–999 employees	95	12.8
1000 employees and more	116	15.6
Specialization		
General	520	70.0
Specialized	223	30.0
Ownership status		
Public	317	42.7
Non-profit	97	13.1
Private	318	42.8
Missing values	11	1.4
Total	743	100

Model specification

As dependent variables for the innovation equations we use two binary variables, one for product innovation (INNOPD) and a second one for process innovation (INNOPC; see Table 3 for the definition of the variables). As performance variables we use three measures that are based on assessments of the hospitals themselves of the impact of ICT use on (1) revenue growth (PERF1); (2) the efficiency of hospital processes (PERF2);[8] and (3) the quality of patient care (PERF3).[9] These three measures cover important aspects of hospital performance and two of them are hospital-specific. Since we do not have 'objective'

[6] For a short descriptive analysis of the results of the 2006 survey for hospitals see European Commission [22].

[7] We refrain here from also investigating ICT-based financial services because almost all European hospitals have such ICT applications since many years (see [22]).

[8] The efficiency can be measured, e.g., by the relationship between the number of patient days in hospital and indicators of ICT use (see, e.g., [6]).

[9] The quality of health care can be measured, e.g., by patient mortality, medical complication cases and readmission rates (see, e.g., [1]).

Table 2 Frequency of various ICT applications used in European hospitals

ICT applications	*N*	Percentage
Hospital-specific		
Patient administration system	600	80.8
Radiology information systems (RIS)	317	42.7
Picture archiving systems (PACS) and medical image transmission	246	33.1
Pharmacy management system	437	58.8
Electronic transmission of prescriptions	154	20.7
Computerized physician order entry (CPOE)	250	33.7
Medical records management	501	67.4
General		
Intranet	454	61.1
E-knowledge management software	158	21.3
Enterprise resource planning system (ERP)	224	30.2
Supply change management system (SCM)	139	18.7
Customer relationship management (CRM)	82	11.0

quantitative measures of hospital performance, we utilize the above mentioned available 'subjective' ones in order to extract a pattern of factors, particularly of ICT-related factors, that are closely associated with ICT-enabled performance. This will allow us to identify which dimensions/factors, are responsible for the impact of ICT on performance that is reported by the hospitals, and also to test our research hypothesis 3 concerning the impact of innovation on it.

As explanatory variables we use for both categories of dependent variables (innovation, ICT-enabled performance) two groups of measures: ICT-related variables and controls for several general characteristics of hospitals that might be relevant for innovation or the performance dimensions that were taken into consideration in this study (see Table 3 for the definition of the variables).[10]

The first group, which is the most important one, consists of a series of ICT-related variables that cover a wide spectrum of elements of the ICT infrastructure of a hospital.

The variables 'ICT-personnel', 'ICT-invest' and 'ICT-budget' capture various aspects of the resource endowment in ICT. The variables 'e-business' and 'website' refer to ICT supporting the external communication of the hospital.

Eight further variables denote the use of important ICT applications that support internal functions (both 'vertical' ICT applications supporting the tasks of a single department and also 'horizontal' ones supporting the exchange of information among different departments and therefore their horizontal cooperation and coordination—see Table 2). Some of them are specific to the health sector, namely 'patient administration system' (ICT_appl1); 'picture archiving systems' (PACS) (ICT_appl2); 'pharmacy management system' (ICT_appl3); 'computerized physician order entry' (CPOE) (ICT_appl4) and 'medical records management system' (ICT_appl6); some others are of more general use (across departments) such as 'intranet' (ICT_appl5); 'enterprise resource planning system' (ERP) (ICT_appl7) and 'customer relationship management' (CRM) (ICT_appl8). The survey provided information also for four further applications, both sector-specific and general ones: 'radiology information systems' (RIS); 'knowledge management software'; 'electronic transmission of prescriptions' and 'supply change management' (SCM). Dummy variables for these four further applications were tested in all five models and found to be statistically insignificant. For this reason they were not further pursued in our study. But it is relevant information with respect to the factors that influence innovation and/or performance in hospitals to know which type of ICT-applications yields significant effects, and which does not, in our innovation equation and performance equations, respectively.

Finally, we also included measures of interoperability of hospital's ICT-systems. Interoperability is quite important for the efficient use of ICT and the maximization of

[10] In terms of economic concepts, the innovation equations should also include some measures of demand for hospital services and appropriability (of innovation returns) (see, e.g., [2] for the service sector). We do not have such measures but the risk of omitted variable bias is small because for public and non-profit hospitals, i.e. for the largest part of European hospitals, demand and protection from imitation of competitors are not important drivers of innovation, or at least not so important as in private enterprises. Further, the performance equations should contain in terms of augmented production (productivity) functions a measure of physical capital. No such measure could be found in our data with the exception of the number of beds that has been used as a proxy for hospital capital in the empirical literature (see, e.g, [6]). We tested this variable in our models and found no significant correlation with any of our performance variables. Because of the relatively high correlation of this variable with firm size ($r = 0.64$) we refrained from keeping it in our model. Thus, firm size, which is included in our models, seems to control to some extent also for physical capital.

Table 3 Definition of the variables

Variables	Definition
INNOPD	Introduction of new or substantially improved products or services in the past 12 months: yes/no
INNOPC	Introduction of new or substantially improved internal processes in the past 12 months: yes/no
PERF1	Positive revenue growth due to ICT use: yes/no
PERF2	Positive influence of ICT use on the efficiency of hospital processes: yes/no
PERF3	Positive influence of ICT use on the quality of patient care: yes/no
R&D	Employees conducting research and development: yes/no
ICT_personnel	Employment of ICT practitioners yes/no
ICT_investment	Investment in ICT (for new hardware, software or networks) in the past 12 months
ICT_budget	Increase of ICT budget in the past 12 months yes/no
Website	Website on the internet: yes/no
E-business	E-business is a significant part of the way a hospital operates: yes/no
ICT_appl1	Use of patient administration system: yes/no
ICT_appl2	Use of picture archiving systems (PACS) and medical image transmission: yes/no
ICT_appl3	Use of pharmacy management system: yes/no
ICT_appl4	Use of computerized physician order entry (CPOE): yes/no
ICT_appl5	Use of intranet: yes/no
ICT_appl6	Use of medical records management: yes/no
ICT_appl7	Use of enterprise resource planning system (ERP): yes/no
ICT_appl8	Use of customer relationship management (CRM): yes/no
ICT_interoper1	Use of XML-based standards (such as ebXML, RosettaNet, UBL): yes/no
ICT_interoper2	Use of health level 7 standard: yes/no
ICT_competition	Increase of competition in the health sector due to ICT: yes/no
General hospital	General hospital: yes/no; reference: specialized hospital
Public hospital	Public hospital: yes/no; reference: private hospital
Non-profit hospital	Non-profit hospital; reference: private hospital
Founded after 1981	Founded before 1981: yes/no
Dummies for hospital size	Dummies for five size classes (number of employees); reference: 10–49 employees
Country dummies	Belgium, Czech Republic, Germany, Greece, Spain, France, Italy, Latvia, Lithuania, Hungary, The Netherlands, Poland, Portugal, Finland, Sweden, Turkey, Norway

benefits from it [33], as it allows the easy and low cost exchange of data and business documents with suppliers, other hospitals and health centers, etc. We exploited information on the use of 'XML-based standards' (i.e. 'horizontal' standards for exchanging data and business documents with any kind of other organizations), and 'Health Level 7 standards' (i.e. 'vertical' standards that can be used for exchanging data within the healthcare sector, specific to the needs of this sector).

The controls included variables for the (ICT-driven) competition conditions among hospitals, the type of hospital (general or specialized), the ownership status (public, non-profit, private), the hospital age, the size of the hospital and the country to which a hospital belongs.

We specified and estimated econometrically five equations: one for product innovation, one for process innovation and three equations for the three different dimensions of hospital performance that are taken into consideration in this study. All five equations included the above-mentioned right-hand variables; the performance equations included in addition the two innovation measures.

Results

Econometric issues

Activities directed to product innovation and those aiming at process innovation are closely related (see, e.g., [5] for a theoretical justification of this close complementary relationship; [29, 42] for empirical evidence). In order to take this interdependence into account we estimated a bivariate probit model for the binary variables INNOPD and INNOPC.

Due to the cross-sectional 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 both the innovation and the performance equations have to be seen primarily as an extensive analysis of the correlations between the determinants (that are considered as structural characteristics that change only slowly over time) and the innovation and performance indicators, respectively. Nevertheless, some robust regularities come out which, if interpreted in view of our hypotheses presented in "Research hypotheses", could possibly indicate the direction of causal links.

However, as a control of the robustness of our results with respect to the relationship between innovation and performance, we tested endogeneity of the variables INNOPD and INNOPC in the three performance equations by applying the procedure by Rivers and Vuong [41]. Instrument equations were estimated separately for each of the two innovation variables. The instrument choice was based on three criteria: significant correlation to the instrumented variables, insignificant correlation to the dependent variables and insignificant correlation to the error term of the performance equation. The residuals (predicted instrumented variables minus original variables) of the first stage instrument equations were inserted in the innovation equation as additional right-hand variables. Bootstrapping was used to correct the standard errors of the estimated parameters. If the coefficient of the residuals was statistically significant (at the 10 % test level), we have assumed that endogeneity is a problem and consequently based our inference on instrumented variables; also in this case standard errors were estimated by bootstrapping. In cases in which the coefficient of the residual was not statistically significant, we have assumed exogeneity of the innovation variables and the estimates were based on the original variables. On the whole, we tested six estimates (two different right-hand variables for three performance indicators). Only the residual for INNOPD in the PERF3-equation was statistically significant (hint for endogeneity of INNOPD). In this case, instead of the original variable, we inserted the predicted value of INNOPD in the PERF3-equation.[11] All right-hand variables in our model are dummy variables, so that we can compare directly the relative magnitude of the various effects without the calculation of marginal effects as it is usually done.

Innovation equations

Table 4 shows the bivariate probit estimates for the two innovation equations. The overall picture that emerges from our estimates is that ICT-related factors are closely related with the innovation performance of European hospitals. However, there are also some differences between product and process innovations. The high correlation between the two innovation equations ($\rho = 530$ in Table 4) seems to justify the application of multivariate probit as the appropriate econometric method in order to take into account the interdependence between these two forms of innovation.

The further expansion of the ICT infrastructure through additional investment in hardware, software or networks shows a significantly positive effect on the propensity of both product and process innovation (ICT_investment). The increase of the effective ICT budget (ICT_budget), which is used not only for ICT investment but also for ICT operating expenses, appears to have a positive effect, particularly on process innovation that mostly requires larger ICT operating expenses than product innovation.

The impact of ICT infrastructure on innovation is not directly associated with the employment of ICT specialists (ICT_personnel). This is not in agreement with previous empirical literature based on datasets for manufacturing and service firms, which conclude that the employment of ICT personnel increases considerably the positive effects of ICT infrastructures on innovation (e.g., [4]). Presumably, the ICT personnel of hospitals focus mainly on the efficient operation of their ICT infrastructures, and not on exploring novel ways of exploiting them for promoting product or process innovation, which in this sector requires mainly extensive medical knowledge and expertise.

The existence of a website is not important for innovation, but external links mostly for e-collaboration, exchange of information and on-line sourcing seem to be relevant for both forms of innovation (E_business).

The use of four out of the twelve examined ICT applications is positively correlated with either product or process innovation or with both of them. These are PACS, CPOE, ERP and CRM. The two hospital-specific applications picture archiving and communication system (PACS) and computerized physician order entry (CPOE) are relevant for both types of innovation. Both these applications allow the exchange and combination of data and knowledge between personnel of different functions/departments of the hospital, which is, according to the literature, of critical importance for product innovation (see, e.g., [39]); also, they enable a better horizontal cooperation and coordination between different functions/departments, so they drive innovations in processes. In particular, CPOE enables physicians' orders for various examinations to be automatically transmitted electronically—through hospital's internal network—to the corresponding hospital laboratories. This, on one hand, eliminates previous lengthy, problematic (e.g., because of faults and losses) and inefficient paper-based processes followed for this purpose, and on the other hand allows a better planning of laboratories' work and resources exploitation. CPOE also enables

[11] The detailed results are available upon request.

Table 4 Effects of ICT on innovation; multivariate probit estimates

	INNOPD	INNOPC
R&D	0.199 (0.128)	0.202* (0.124)
ICT_personnel	0.081 (0.121)	0.116 (0.123)
ICT_investment	0.538*** (0.153)	0.304* (0.160)
ICT_budget	0.091 (0.118)	0.272** (0.118)
Website	0.040 (0.144)	0.061 (0.147)
E-business	0.235* (0.126)	0.292** (0.137)
ICT_appl2	0.222* (0.125)	0.303** (0.130)
ICT_appl4	0.355*** (0.131)	0.378*** (0.133)
ICT_appl7	0.068 (0.129)	0.307*** (0.127)
ICT_appl8	0.489*** (0.175)	0.029 (0.178)
ICT_interoper1	−0.010 (0.141)	0.282** (0.140)
ICT_interoper2	0.388** (0.161)	0.253* (0.153)
ICT_competition	0.266** (0.118)	0.357*** (0.119)
General hospital	0.203 (0.132)	−0.180 (0.132)
Public hospital	−0.186 (0.166)	−0.045 (0.162)
Non-profit hospital	−0.021 (0.197)	−0.082 (0.186)
Founded after 1981	−0.102 (0.126)	−0.058 (0.128)
50–99 employees	0.070 (0.213)	0.072 (0.206)
100–199 employees	−0.038 (0.204)	0.119 (0.197)
200–499 employees	0.007 (0.210)	−0.082 (0.208)
500–999 employees	−0.008 (0.253)	−0.094 (0.248)
1000 employees and more	−0.024 (0.261)	−0.147 (0.262)
Country dummies	Yes	Yes
Const.	−1.704*** (0.359)	−1.381*** (0.345)
N	678	
Wald χ^2	324.9***	
Rho	0.530	
Wald χ^2 test of $\rho = 0$	66.4***	

Heteroskedasticity-robust standard errors in brackets

Reference 'general hospital': 'specialized hospital'; reference 'public' and non-profit': 'private'; reference hospital size: 10–49 employees

***, **, * Statistical significance at the 1, 5 and 10 % test level, respectively

the results of these examinations to be transmitted back to the physicians electronically, and possibly stored in patients' electronic medical records as well, so that the appropriate medical actions can be taken much quicker than before; these lead finally to higher efficiency and effectiveness. Similarly, PACS allows the pictures (images) produced from various medical examinations to be centrally archived and linked with patients' electronic medical records, so they are directly accessible by clinics and physicians throughout the hospital, in order to be exploited to the largest possible extent for supporting medical decisions (e.g., concerning a patient's optimal therapy); this also results in higher efficiency and effectiveness.

From the two applications of general use, the enterprise resource planning system (ERP) is important for process innovation, and customer relationship management (CRM) for product innovation, quite in accordance with the specific application fields of these ICT technologies in other types of organizations or firms.

We would expect that the use of e-knowledge management software would contribute to innovation, but testing of this variable showed that this was not the case. Further, it is not astonishing that applications serving primarily administrative and managerial purposes such as patient administration systems, pharmacy management systems and electronic transmission of prescriptions (see Table 2), which were also tested as right-hand variables, do not contribute to innovation performance. It is also not surprising that supply change management system (SCM) was not significantly correlated with product or process innovation (also tested as right-hand variable), because the logistics of material inputs and intermediate products is not so important for a hospital as, e.g., for the production organization of an enterprise.

Another interesting finding is that the establishment of interoperability of hospitals' ICT systems with those of cooperating organizations through the adoption of interoperability standards, has positive effects on innovation. This interoperability facilitates the exchange of data and knowledge with other organizations, which according to the literature promotes innovation (e.g., [14, 39, 49]). The adoption of the 'vertical' health sector HL7 standards seems to have the strongest positive effects on both product and process innovation, while the adoption of the 'horizontal' XML-based standards that are not hospital-specific have weaker effects only on process innovation. An explanation for this difference is presumably that HL7 standards are specific and enable a 'deep' interoperability and extensive exchange of highly detailed clinical and administrative data and knowledge with the organizations that are most important for innovation, and this has a strong positive impact on innovation performance.

R&D activities provide inputs for innovations. The existence of such activities is, as expected, positively correlated with both types of innovation, but the respective coefficient is statistically significant only in the process innovation equation. This indicates that a hospital's R&D focuses on processes innovation, while product innovation is probably mainly a task of its individual clinical department, as it requires specialized medical knowledge and expertise.

Also our (ICT-specific) competition variable correlates positively with both types of innovation, in accordance with similar findings in empirical innovation studies (see [15] for a survey of this literature).

A further interesting finding is that the size of hospitals as measured by the number of employees does not show any effect on innovation. This is contrary to results of similar studies for industries of business services, in which mostly a significant (mostly positive) correlation of firm size and some innovation indicator is found (see, e.g., [2]); therefore, scale does not seem to be particularly important for innovation in hospitals.

Finally, a series of general hospital characteristics (general or specialized; owner status; hospital age) that serve as controls also do not seem to have any influence on innovation performance.

Performance equations

Table 5 shows the models estimated for the three performance variables. There are significant differences between the estimates. Most of them refer to different effects of the 12 specific ICT applications taken into consideration in this study.

One first important result refers to the role of innovation. ICT-enabled revenue growth correlates positively with both product and process innovation. This indicates that revenue growth generated by ICT applications could be reinforced through the introduction of new or improved services (perhaps themselves enabled by IT), for example in the field of patient care, and increase the attractiveness of a hospital for additional patients. Parallel to this, the increase of efficiency in the hospital processes due, for example, to the introduction of new organizational modes would also contribute to (ICT-enabled) revenue growth. The effects of innovation on revenue growth can be considered in the light of the results in Table 4 also as indirect effects of ICT on revenue growth, beyond the direct effects in Table 5 which are discussed in the following paragraphs. This is also substantiated by the way we endogenized the innovation variables using the specification in Table 4. The other two performance measures, PERF2 and PERF3, are cost- and quality-oriented, so it is understandable that they are significantly correlated only with the measure for process innovation.

Based on the results for the various ICT-oriented variables, a pattern of the specific ICT elements that correlate with each of the three measures of ICT-enabled performance used in this study emerges. We interpret these specific ICT elements as the ones that enable the respective performance effects. The use of Website is the only element of the ICT infrastructure that seems to be important for all three performance variables. This indicates that though hospitals' websites are not important for their innovation activity (see "Innovation equations"), they contribute positively to hospitals' revenue, processes efficiency, and quality of patient care (increasing the impact of hospital's ICT on these important performance dimensions). For PERF2 (efficiency of hospital services) besides process innovation and R&D, practically all elements of ICT infrastructure (variables ICT_personnel; ICT_investment; E-business) show a significantly positive effect. In contrast, for PERF1 (revenue growth) only a strategy of general increase of ICT budget is relevant, while for PERF3 (quality of patient care) only ICT personnel seems relevant (as for the quality of patient care, it is important to have high levels of maintenance of all elements of ICT infrastructures and applications, and also a high level of exploitation of even their most sophisticated capabilities, which require specialized ICT personnel).

The use of PACS seems to enhance both the revenue and the efficiency of hospital processes (see also [8] for a positive effect of PACS use on a hospital's market share). Revenue growth is further positively correlated with the use of medical records management and CRM, while efficiency is positively correlated with the use of intranet and a pharmacy management system. The only application that appears to correlate positively with PERF3 (quality of patient care) is medical records management.

Table 5 Effects of ICT on performance measures; probit estimates

	PERF1	PERF2	PERF3
INNOPD	0.281** (0.128)	−0.125 (0.143)	−0.003 (0.143)
INNOPC	0.371*** (0.126)	0.329*** (0.132)	0.293** (0.134)
R&D	0.042 (0.123)	0.340** (0.141)	0.05 (0.142)
ICT_personnel	0.114 (0.122)	0.464*** (0.127)	0.357*** (0.133)
ICT_investment	0.153 (0.158)	0.321** (0.154)	0.089 (0.148)
ICT_budget	0.270** (0.117)	0.116 (0.128)	0.126 (0.130)
Website	0.408*** (0.145)	0.350** (0.146)	0.319** (0.152)
E-business	−0.051 (0.141)	0.269* (0.160)	0.031 (0.159)
ICT_appl1			0.321** (0.163)
ICT_appl2	0.222* (0.132)	0.247* (0.148)	
ICT_appl3		0.237* (0.142)	
ICT_appl5		0.247** (0.125)	
ICT_appl6	0.236* (0.125)		0.307** (0.133)
ICT_appl8	0.276* (0.166)		
ICT_interoper1		0.479** (0.222)	0.378* (0.214)
IKCT_interoper2		0.392** (0.172)	
ICT_competition	0.293*** (0.118)	0.153 (0.124)	0.128 (0.127)
General hospital	0.330** (0.132)	0.068 (0.138)	−0.083 (0.142)
Public hospital	−0.195 (0.169)	−0.345** (0.176)	−0.282 (0.184)
Non-profit hospital	−0.230 (0.203)	−0.312 (0.211)	−0.395* (0.214)
Founded after 1981	−0.129 (0.125)	0.134 (0.131)	−0.135 (0.142)
50–99 employees	0.714*** (0.218)	0.193 (0.214)	0.363* (0.217)
100–199 employees	0.211 (0.201)	0.191 (0.218)	0.357* (0.206)
200–499 employees	0.587*** (0.201)	0.280 (0.224)	0.833*** (0.209)
500–999 employees	0.532** (0.234)	0.268 (0.268)	1.004*** (0.209)
1000 employees and more	0.515** (0.242)	0.078 (0.280)	0.562** (0.268)
Country dummies	Yes	Yes	Yes
Const.	−2.095*** (0.362)	−1.260*** (0.352)	−0.870** (0.367)
N	678	678	678
Pseudo R^2	0.203	0.247	0.182
Wald χ^2	167.1***	180.4***	123.5***

Heteroskedasticity-robust standard errors in brackets

Reference 'general hospital': 'specialized hospital'; reference 'public' and non-profit': 'private'; reference hospital size: 10–49 employees

***, **, * Statistical significance at the 1, 5 and 10 % test level, respectively

Agha [1] found only partial evidence for a positive impact of ICT on the quality of patient healthcare in USA hospitals 5 years after the adoption of the ICT applications that were taken into consideration in this study. Also, McCullough et al. [36] found only partial evidence of positive effects of medical records management and CPOE on certain patient outcomes (four common, high mortality illness conditions).

As compared with the findings for the innovation variables, the use of CPOE and ERP seems to be of no relevance for all three performance variables (though it is for innovation): partly contrary, partly in accordance with existing USA empirical literature [35, 36]. Finally, four applications that were tested as right-hand variables in all five estimated equations showed no significant effects at all: radiology information systems (RIS), electronic

transmission of prescriptions, e-knowledge management software and supply change management system (SCM). For some of them the reason for not showing any effect may be that their use until now has not yet exploited their potential (e.g., RIS), or that their use is not widespread because they are not necessary for hospital operation (e.g., SCM).

Interoperability of hospitals' information systems is relevant only for cost- and quality-oriented performance measures (PERF2 and PERF3) but not for revenue growth (PERF1).

The existence of R&D activities is important only for PERF2, but not important for PERF1 and PERF3 (which indicates that R&D focuses mainly on processes efficiency, in agreement with the findings presented in "Innovation equations"), while ICT_competition shows a positive effect only for revenue growth (PERF1). There are some size effects but they are not monotonic in either direction, so that no patterns having some regularity are discernible. Finally, we found that private hospitals do better than public hospitals in terms of exploiting their information systems for increasing efficiency of processes, and also do better than non-profit hospitals in terms of exploiting their information systems for quality of patient healthcare (see [31] for a similar effect in the USA hospitals). General hospitals seem to be better than specialized hospitals in terms of information systems exploitation for increasing revenue growth. No effect could be found for hospital age.

Summary and conclusions

The above results confirm all three research hypotheses referring to positive effects of ICT on hospital innovation, as well as the effects of the latter on three measures of ICT-enabled performance (revenue growth, efficiency of hospital processes, and quality of patient care). In addition to ICT, innovation also correlates positively with the (ICT-enabled) performance measures, and as a consequence, (1) innovation seems to reinforce the ICT impact on performance, and (2) ICT shows not only direct but also indirect positive effects, via innovation, on hospital performance. There are also interesting findings with respect to the (differing) effectiveness of 12 important ICT applications, among them some that were extensively investigated in USA studies (PACS, CPOE and medical records management).

In particular, we have identified four types of 'horizontal' cross-departmental applications that have a positive impact either on product or on process innovation or on both, which, however, are not widely used. Two of them are healthcare-specific: picture archiving and communication systems (PACS) and computerized physician order entry (CPOE), both showing positive effects on product and on process innovation. The other two are more general: ERP has a positive impact on process innovation, and CRM has a positive impact on product innovation. In contrast, we have found that some other 'vertical' applications that primarily support the administrative and managerial tasks of a single department, such as patient administration and pharmacy management systems, do not contribute to innovation performance. Also, our results indicate that the use of e-business applications by hospitals has a positive impact on both product and process innovation. This type of application shares with the above mentioned four applications (that positively affect innovation activity) one other important feature: they enable the horizontal exchange and combination of data and knowledge with hospital's external environment which, according to previous innovation literature, also promotes innovation.

Furthermore, it has been concluded that establishment of interoperability of hospitals' ICT systems with those of other cooperating organizations, through the adoption of interoperability standards, has positive effects on innovation.

Finally, we have identified six types of applications that have positive impact on some of the performance measures, most of them being applications that support primarily administrative and managerial tasks. Only two of them are among the ones having positive impact on innovation, while the other four do not contribute to innovation. This indicates that in the hospital context there are some ICT applications contributing directly to performance (we can call them 'performance applications'), some other applications having positive impact on innovation (and through it indirect impact on performance) (we can call them 'innovation applications'), and some others impacting positively on both performance (directly) and innovation (we can call them 'dual applications').

A further important result refers to the role of innovation. ICT-enabled revenue growth correlates positively with both product and process innovation. Therefore, revenue growth generated by ICT applications could be reinforced through the introduction of new or improved

services (perhaps themselves enabled by IT), for example in the field of patient care, and increase the attractiveness of a hospital for additional patients. Parallel to this, the increase of efficiency in the hospital processes due, for example, to the introduction of new organizational modes would also contribute to (ICT-enabled) revenue growth.

Our findings have interesting implications for research. With respect to future research on the impact of ICT on innovation and (ICT-enabled) performance (in the health sector and in other sectors as well) our findings indicate that it should not view ICT as a single entity, but should, on the contrary, discriminate between various aspects of it, such as different types of ICT applications and interoperability standards, which might have quite different effects. Our study provides a framework in this direction.

Of course there are also drawbacks in our study. The study is a cross-sectional analysis and uses rather crude measures of quality of patient healthcare or of efficiency of processes. It refers only to European hospitals, and it is possible that our findings do not hold for hospitals in other regions. Moreover, no information on the time of adoption of various ICT elements is available. Thus, our estimates of the positive correlations of ICT use with the left-hand measures of innovation and performance can be considered as rather lower bounds of the respective effects. This is because for some hospitals that have adopted these technologies recently, not enough time has elapsed to be able to fully exploit the potential of the new technologies. So further research is required for investigating the main questions of this study in other contexts as well (beyond Europe, in other regions), using more sophisticated measures of patient healthcare quality or process efficiency, and probably examining new types of ICT such as, e.g., data warehousing and social media, and based on panel data.

Appendix

See Tables 6 and 7.

Table 6 Descriptive statistics of the model variables ($N = 678$)

Variables	Mean	Standard error
INNOPD	0.425	0.019
INNOPC	0.479	0.019
PERF1	0.406	0.019
PERF2	0.684	0.018
PERF3	0.767	0.016
R&D	0.440	0.019
ICT_personnel	0.500	0.019
ICT_investment	0.822	0.015
ICT_budget	0.378	0.019
Website	0.757	0.016
E-business	0.248	0.017
ICT_appl1	0.804	0.015
ICT_appl2	0.329	0.018
ICT_appl3	0.587	0.019
ICT_appl4	0.333	0.018
ICT_appl5	0.609	0.019
ICT_appl6	0.673	0.018
ICT_appl7	0.301	0.018
ICT_appl8	0.115	0.012
ICT_interoper1	0.230	0.016
ICT_interoper2	0.237	0.016
ICT_competition	0.547	0.019
General hospital	0.700	0.017
Public hospital	0.412	0.019
Non-profit hospital	0.134	0.013
Founded after 1981	0.597	0.019

Table 7 Correlation matrix

	ICT_ personnel	ICT_ investment	ICT_ budget	E-business	Website	ICT_ appl1	ICT_ appl2	ICT_ appl3	ICT_ appl4	ICT_ Inter per1	ICT_ Inter per2	R&D	ICT_ Compe-tition	General hospital	Public hospital	Non-Profit hospital	Founded 1981	INNOPD
ICT_personnel	1.000																	
ICT_investment	0.250	1.000																
ICT_budget	0.037	0.133	1.000															
E-business	0.103	0.045	0.067	1.000														
Website	0.113	0.176	0.023	0.079	1.000													
ICT_appl1	0.179	0.089	−0.001	0.085	0.148	1.000												
ICT_appl2	0.056	0.076	0.043	0.022	0.153	0.204	1.000											
ICT_appl3	0.090	0.029	−0.013	0.033	0.005	0.171	0.225	1.000										
ICT_appl4	0.111	0.047	0.053	0.029	0.129	0.013	0.108	0.066	1.000									
ICT_interoper1	0.189	0.081	0.000	0.043	0.139	0.184	0.015	0.054	0.143	1.000								
ICT_interoper2	0.267	0.142	0.059	0.129	0.220	0.273	0.025	0.087	0.092	0.239	1.000							
R&D	0.137	0.017	0.052	0.056	0.066	0.120	0.074	−0.004	0.072	0.095	0.037	1.000						
ICT_competition	0.145	0.102	0.116	0.076	0.106	0.120	0.132	0.022	0.012	0.054	0.027	0.209	1.000					
General hospital	0.103	0.044	0.071	0.052	−0.009	0.121	0.127	0.084	−0.003	0.056	0.030	0.010	0.063	1.000				
Public hospital	0.123	0.053	−0.015	−0.029	0.057	0.065	−0.006	−0.006	0.009	0.170	0.055	0.063	0.032	0.142	1.000			
Non-profit hospital	0.004	−0.031	0.006	0.075	0.022	0.028	−0.021	−0.023	−0.047	−0.010	0.106	0.000	0.019	−0.003	−0.329	1.000		
Founded after 1981	0.087	0.081	−0.049	0.081	0.031	0.031	−0.045	0.047	0.023	0.042	0.190	−0.121	−0.052	0.125	0.173	0.076	1.000	
INNOPD	0.155	0.175	0.131	0.067	0.077	0.173	0.203	0.041	0.186	0.105	0.074	0.177	0.218	0.140	0.076	−0.006	−0067	1.000
INNOPC	0.162	0.193	0.136	0.140	0.125	0.208	0.205	0.149	0.070	0.128	0.165	0.102	0.226	0.024	−0.064	0.029	0.005	0.418

References

1. Agha, L.: The effects of health information technology on the costs and quality of medical care. MIT economics working paper, Cambridge (2012)
2. Arvanitis, S.: Explaining innovative activities in service industries: micro data evidence for Switzerland. Econ. Innov. New Technol. **17**(3), 209–225 (2008)
3. Arvanitis, S., Loukis, E., Diamantopoulou, V.: Are ICT, workplace organization and human capital relevant for innovation? A comparative study based on Swiss and Greek micro data. KOF Working Papers No. 333, Zurich (2013)
4. Arvanitis, S., Loukis, E., Diamantopoulou, V.: The effect of soft ICT capital on innovation performance of Greek firms. J. Enterp. Inf. Manag. **26**(6), 679–701 (2013)
5. Athey, S., Schmutzler, A.: Product and process flexibility in an innovative environment. Rand J. Econ. **26**, 557–574 (1995)
6. Atkinson, B.R., Cockerill, T.: Information technology implementation and efficiency in the US hospital sector 1997–2001: a production function approach. Paper presented in the International Industrial Organization Conference, Northeastern University, Boston, 2006
7. Baltagi, B.H., Moscone, F., Tosetti, E.: Medical technology and the production of health care. Empir. Econ. **42**(2), 395–411 (2012)
8. Barrette, E., McCullough, J., Town, R.: The impact of health information technology on hospital demand. Working Paper (2011)
9. Biagi, F., Parisi, M.L.: Are ICT, human capital and organizational capital complementary in production? Evidence from Italian panel data. JRC Technical Reports, Institute for Prospective Technological Studies, European Union, Seville (2012)
10. Borzekowski, R.: Measuring the cost impact of hospital information systems: 1987–1994. J. Health Econ. **28**, 938–949 (2010)
11. Bresnahan, T.F., Brynjolfsson, E., Hitt, L.M.: Information technology, workplace organisation, and the demand for skilled labour: firm-level evidence. Quart. J. Econ. **112**(1), 339–376 (2002)
12. Brynjolfsson, E., Saunders, A.: Wired for innovation: how information technology is reshaping the economy. MIT Press, Cambridge (2010)
13. Buntin, M., Burke, M., Hoaglin, M., Blumenthal, D.: The benefits of health information technology: a review of the recent literature shows predominantly positive results. Health Aff. **30**, 464–471 (2011)
14. Castellaci, F.: Technological paradigms, regimes and trajectories: manufacturing and service industries in a new taxonomy of sectoral patterns of innovation. Res. Policy **37**, 978–994 (2008)
15. Cohen, W.M.: Fifty years of empirical studies of innovative activity and performance. In: Hall, B.H., Rosenberg, N. (eds.) Handbook of the economics of innovation, vol. 1, pp. 129–213. Elsevier B.V, Amsterdam (2010)
16. Cunningham, P.: Innovation in the health sector—case study analysis. Publin Report No. D19, NIFU STEP, Oslo (2005)
17. Crèpon, B., Duguet, E., Mairesse, J.: Research, innovation and productivity: an econometric analysis at the firm level. Econ. Innov. New Technol. **7**, 115–156 (1998)
18. Cutler, D., Feldman, N., Horowitz, J.: US adoption of CPOE. Health Aff. **24**, 1654–1663 (2005)
19. Djellal, F., Gallouj, F.: Mapping innovation dynamics in hospitals. Res. Policy **34**, 817–835 (2005)
20. Djellal, F., Gallouj, F.: Innovation in hospitals: a survey of the literature. Eur. J. Health Econ. **8**, 181–193 (2007)
21. Enkel, E., Gassmann, O., Chesbrough, H.: Open R&D and open innovation: exploring the phenomenon. R&D Manag. J. **39**(4), 311–316 (2009)
22. European Commission: European e-business report, Ch. 'Hospital activities industry', pp. 187–196 (2007)
23. Gretton, P., Gali, J., Parham, D.: The effects of ICTs and complementary innovations on Australian productivity growth. Productivity Commission, Canberra (2003)
24. Hall, B.H., Lotti, F., Mairesse, J.: Evidence on the impact of R&D and ICT investments on innovation and productivity in Italian firms. Econ. Innov. New Technol. **22**(3), 300–328 (2012)
25. Hempell, T., van Leeuwen, G., van der Wiel, H.: ICT, Innovation and business performance in services: evidence for Germany and the Netherlands. ZEW working paper No. 04-06, Mannheim, Germany (2004)
26. Jha, A.K., Dolan, D., Grandt, D., Scott, T., Bates, D.W.: The use of health information technology in seven nations. Int. J. Med. Inform. **77**, 848–854 (2008)
27. Kleis, L., Chwelos, P., Ramirez, R., Cockburn, I.: Information technology and intangible output: the impact of IT investment on innovation productivity. Inf. Syst. Res. **23**(1), 42–59 (2012)
28. Klevorick, A.K., Levin, R.C., Nelson, R.R., Winter, S.G.: On the sources and significance of interindustry differences in technological opportunities. Res. Policy **24**, 185–205 (1995)
29. Kraft, K.: Are product and process innovations independent of each other? Appl. Econ. **12**, 1029–1038 (1990)
30. Laursen, K., Salter, A.: Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms. Strateg. Manag. J. **27**, 131–150 (2006)
31. Lee, J., McCullough, J.S., Town, R.J.: The impact of health information technology on hospital productivity. NBER Working Papers No. 18025, Cambridge (2012)
32. Lichtenberg, F.R.: The impact of therapeutic procedure innovation on hospital patient longevity: evidence from Western Australia, 2000–2007. Soc. Sci. Med. **77**(C), 50–59 (2013)
33. Loukis, E., Charalabidis, Y.: An empirical investigation of information systems interoperability business value in European firms. Comput. Ind. **64**(4), 412–420 (2013)
34. McCullough, J.S.: The adoption of hospital information systems. Health Econ. **17**, 649–664 (2008)
35. McCullough, J.E., Casey, M., Moscovice, I., Prasad, S.: The effect of health information technology on quality in US hospitals. Health Aff. **29**, 647–654 (2010)
36. McCullough, J., Parente, S., Town, R.: The impact of health information technology on patient outcomes. Working Paper (2011)
37. Mikalef, P., Batenburg, R.: Determinants of IT adoption in hospitals—IT maturity surveyed in an European context. In: Proceedings of the International Conference on Health Informatics, Italy, 26–29 January 2011
38. Mohnen, P., Hall, B.H.: Innovation and productivity: an update. Eurasian Bus. Rev. **3**(1), 47–65 (2013)
39. Nerkar, A., Paruchuri, S.: Evolution of R&D capabilities: the role of networks within a firm. Manag. Sci. **51**(5), 575–580 (2005)
40. PwCW: Information technology and hospital performance—an econometric analysis of costs and quality. White Paper, Pricewaterhouse Coopers (2007)
41. Rivers, D., Vuong, Q.H.: Limited information estimators and exogeneity tests for simultaneous probit models. J. Econom. **39**, 347–366 (1988)
42. Rouvinen, P.: Characteristics of product and process innovators: some evidence from Finnish innovation survey. Appl. Econ. Lett. **9**, 575–580 (2002)
43. Salge, T.O.: The temporal trajectories of innovative research: insights from public hospital services. Res. Policy **41**, 720–733 (2012)
44. Skinner, J., Staiger, D.: Technology diffusion and productivity growth in health care. NBER working papers, No. 14865, Cambridge (2009)

45. Stroetmann, K., Artmann, J., Stroetmann, V.: European countries on their journey towards national eHealth infrastructures. Office for Official Publications of the European Communities, Luxembourg (2011)
46. Stroetmann, K.A., Jones, T., Dobrev, A., Stroetmann, V.N.: An evaluation of the economic impact of ten European eHealth applications. J. Telemed. Telecare **13**(S1), 62–64 (2007)
47. Tapscott, D., Ticoll, D., Lowi, A.: Digital capital—harnessing the power of business webs. Harvard Business School Press, Boston (2000)
48. Thakur, R., Hsu, S.H.Y., Fontenot, G.: Innovation in healthcare: issues and future trends. J. Bus. Res. **65**, 562–569 (2012)
49. Zeng, S.X., Xie, X.M., Tam, C.M.: Relationship between cooperation networks and innovation performance of SMEs. Technovation **30**, 181–194 (2010)