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FACTORS OF PKI ADOPTION IN EUROPEAN FIRMS

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Abstract

Public Key Infrastructure (PKI) is an established technology that has been around for more than fifteen years. However, its adoption follows a very slow pace. Previous research, based either on a theoretical analysis of PKI or on specific cases of PKI implementation, has indicated several possible reasons for PKI non-adoption. In this paper we examine the effect of specific organizational factors on PKI adoption using empirical data from 14065 European firms collected through the e-Business Watch Survey of the European Commission. We have shown that it is still addressed as innovative technology that requires an innovation culture. Moreover, small and medium –sized firms are rather reluctant to adopt it and it is mostly implemented in firms with a large number of employees and tele-workers. Also, the extensive use of IS for supporting internal functions and cooperation with the external environment (e.g. customers and prospects), and the high dependence on them, are drivers of PKI adoption.

Keywords: Information security, PKI, adoption factors, information systems, innovation, telework

1. INTRODUCTION

Information security has been one of the top concerns for IS managers, ever since information systems became an integral part of all but a few business functions. The 2010 Ernst & Young Security Survey (Ernst &Young, 2010) indicates that while a commitment to information security exists, organizations still face advanced, persistent threats. The trend towards anywhere, anytime access to information has significantly increased the vulnerability of current information systems. Unsurprisingly, 64 percent of the 1,600 senior executives from 56 countries that participated in the above survey see data protection as one of the top IT risks that has escalated in the current environment.

Public Key Infrastructure (PKI) provides an established solution to manage trust in open systems, like those that permeate modern, borderless organizations. PKI offers a solid technical basis for the most important security functions, including identification, authentication, authorization and non-repudiation. It enables the use of public key cryptography in numerous applications for inter-organizational and intra-organizational use.

PKI has been available for more than fifteen years (ITU-T, 1993). In this period, numerous government and industry initiatives and campaigns for promoting PKI have been launched. Nevertheless, the adoption of PKI has been astonishingly slow. Lopez et al. (2005) examine several reasons that may have led to PKI failure. They have identified *technical reasons* (e.g. technical complexity and certificate revocation inefficiencies), *economic reasons* (e.g. cost of building wide-scale PKI), *legal reasons* (e.g. liability) and *social reasons* (e.g. poor usability of PKI applications and lack of awareness). Nevertheless, lacking empirical data it is rather difficult to assess these factors and to conclude as to which of them are most important.

Gutmann (2002) claims that although PKI has failed to eventuate to any significant degree,

there are instances in which application specific uses of digital certificates can be employed in a manner that avoids the shortcomings of PKI. He suggests that a solution to the problem of PKI use would be "to adapt the PKI design to the real world rather than trying to constrain the real world to match the PKI".

Carayannis and Turner (2006) follow an empirical research approach based on case study research. They analyze two cases: the U.S. Federal Reserve system and Fannie Mae, the largest Mortgage-backed Securities issuer in the U.S. Based on these case studies they identify organizational factors that enable the success of PKI implementation. They conclude that PKI is "…best suited for organizations or industries that require the highest levels of security." They argue that "[s]uccessful PKI implementations have occurred when PKI was implemented in situations where the organizational tasks were most compatible with the characteristics of the technology and where organizations had the automation capability and the commitment to learning the most effective means for using the technology".

The work of Carayannis and Turner (2006), as well as the work of Lopez et al. (2005), has provided an initial investigation of the issue of PKI adoption. Nevertheless, the issue remains largely unexplored. In this paper, we aim to contribute to the analysis of the factors affecting PKI adoption by means of analyzing empirical data provided by an extensive survey of European firms conducted by the e-Business Watch of the European Commission. Our analysis identifies those characteristics of European firms that correlate with the adoption or non-adoption of PKI technology.

In the following section we present the theoretical background and state the hypotheses that have been tested. The third section presents the method we have followed and the data we have used, while the fourth section presents the results of our analysis. Finally, in the last section we present the main conclusions and the issues that remain for further research.

2. THEORETICAL BACKGROUND AND HYPOTHESES

2.1. Overview of PKI

Public key algorithms produce a pair of encryption keys, one of which is kept private, whilst the other is revealed to the public. The public key can be used to encrypt messages that only the owner of the private key can decrypt. In a similar manner, the owner of the private key can "sign" a message by using her private key to encrypt it (to be more accurate, he/she encrypts a hash of the message.); the signature can be verified by any person that has access to the public key by, simply, decrypting the encrypted message, and this provides a confirmation of the sender identity. Thus, public key cryptography can be used to ensure confidentiality, integrity (if the message is altered then the signature is no longer valid) and non-repudiation (the owner of the private key cannot deny having signed the message, unless the private key has been compromised).

Unlike symmetric key encryption algorithms, a public key algorithm does not require a secure initial exchange of one or more secret keys between sender and receiver. This property of public key cryptography allows the exchange of messages between entities that have no pre-established relationship. Therefore, it is essential to have a mechanism that binds public keys with respective user identities. This is achieved through digital certificates. Digital certificates are issued by Certificate Authorities, which serve as trusted third parties that assure the validity of digital certificates. The binding of identities and public keys is established through a registration and issuance process provided by Registration Authorities.

There are several cases where a digital certificate may no longer be trusted. For example, if the private key is disclosed or the certificate authority system is compromised. In this case the digital certificate should be revoked. As a consequence, there is a need for revocation lists to be established and maintained (Wohlmacher, 2000).

This complex system of authorities (e.g. registration and certificate authorities), services (e.g. revocation) and the relevant policies and procedures is what forms a public key infrastructure. It may support intra-organizational systems, especially when they employ a large number of users and, thus, require an efficient process for user authentication and access control. It can also support inter-organizational systems for the exchange of sensitive information and remote collaboration.

The introduction of PKI in an organization requires a significant investment. However, there is no other technology that can offer such a broad range of information security services in a business environment characterized by mobility, openness and diversity. Therefore, initially there were expectations that the PKI market would flourish. For example, according to Datamonitor (1999) the revenues of the PKI market were expected to reach 1.4 billion USD by 2003. This goal was never achieved, as today only a few companies are making a profit from PKI products and services.

2.2. Research hypotheses

Spinellis et al. (1999) have shown that small firms face a significant level of risk, with regard to the use of ICT. Whilst large firms may suffer considerable losses when their ICT systems fail, they also have more resources that would allow them to recover from the loss. On the contrary, small firms lack the necessary redundancy in ICT resources to deal with a security incident.

On the other hand, PKI complexity hinders small and medium sized firms from developing PKI systems, while this is easier for large firms since they have more access to technical expertise. Moreover, the needs for effective and efficient user authentication and access control increase with the number of users (see, e.g., Damiani et al., 2003). As a result, it is expected that large firms, in terms of number of employees, would be more inclined to deploy PKI technology. Therefore, we tested the following hypothesis:

H1: The number of employees of a firm has a positive effect on PKI adoption.

The most common application of PKI is for the authentication of remote users working outside firm's premises. When users access the company systems on-site rarely there is a need for strong authentication techniques. On the other hand, whenever users need to work from remote locations the need for reliable authentication increases. PKI provides a robust solution for remote authentication and, thus, it is expected that companies with many employees working from a distance would be more likely to invest in PKI technology. The above claim can be tested in the form of the following hypothesis:

H2: The number of teleworkers employed in the firm has a positive effect on PKI adoption.

Another aspect regards the extent to which a firm has integrated information technology in its operations. Firms with several diverse systems usually face significant challenges with regard to the management of authentication and authorization in different system domains. In such cases PKI would appear as the obvious solution, as PKI may support Single Sign On (Clercq, 2002) and identity management in multi-domain environments (Bhatti et al., 2007). We tested whether firms that use a wide range of information systems (IS) tend to invest in PKI. We have distinguished two types of systems, those for internal use (i.e. for supporting internal function) and those for supporting cooperation with the external environment (e.g. with customers and prospects). Thus, we tested the following two hypotheses:

H3: Firms that use a wide range of IS for internal use are more likely to adopt PKI technology.

H4: Firms that use IS for supporting cooperation with the external environment are more likely to adopt PKI technology.

It is often the case that ICT have a strong impact on the operations and performance of a firm, so the latter has developed a strong dependence on its ICT infrastructure. Firms may depend

to a considerable extent on their information systems for revenue growth, efficiency of business processes, internal work organization, procurements cost, quality of products and services, quality of customer service and productivity; such firms are expected to invest in security technology. Of course, firms may choose from a variety of security technologies and they may prefer other technologies instead of PKI. Nevertheless, the effect of the level of ICT impact on firm's operations and performance, and therefore firm's dependence on ICT, on PKI adoption should be examined. For this purposes we tested the following hypothesis:

H5: The level of ICT impact on firm's operations and performance has a positive effect on PKI adoption.

Although PKI has been around for more than fifteen years it is still considered an innovative technology (Carayannis, 2006; Gaude, 2007). It is, thus, expected that firms with a culture of innovation would be more likely to adopt PKI. So, finally, we tested the following hypothesis:

H6: Firms that foster innovation are more likely to adopt PKI technology.

In the following we present the results of testing the above hypothesis using regression analysis on survey data provided by the e-Business Watch Survey.

3. METHOD AND DATA

In particular, for testing the above research hypotheses the following regression model has been estimated:

PKIAD = bo + b1*EMPL + b2*TELEW + b3*INT_IS + b4*EXT_IS + b5*ICT_IMP + b6*INNOV (4.1)

having as dependent variable firm-level PKI adoption (PKIAD), and as independent variables firm's number of employees (EMPL), telework adoption (TELEW), and measures of the IS use internally (INT_IS) and for cooperating with external environment (EXT_IS), impact of ICT on firm's operations and performance (DEP) and innovation activity (INNOV).

The above regression model has been estimated using data from 14065 firms collected in the e-Business Watch Survey 2006, which has been conducted by European e-Business Market W@tch (www.ebusiness-watch.org), an observatory organization sponsored by the European Commission. This survey was based on telephone interviews with decision-makers of firms from 29 countries, including the 25 EU Member States, the European Economic Area (EEA) and the Acceding/Candidate Countries. The population targeted by this survey were all active firms of these countries which use computers and have their primary business activity in one of the following ten highly important sectors (from both manufacturing and services): food and beverages, footwear, pulp and paper, ICT manufacturing, consumer electronics, shipbuilding and repair, construction, tourism, telecommunications and hospital activities. From this population a stratified sampling was made with respect to sector and company size (so that firms of all sectors and sizes are included).

In the Appendix are shown the questions of the above survey we used in this study:

- PKI adoption (PKIAD) has been measured through one dichotomous item (yes/no) assessing whether the firm uses PKI or not.

- Similarly, for the number of employees (EMPL) we used one item on this included in the above survey.

- Telework adoption (TELEW) was measured through one dichotomous item (yes/no) assessing whether firm employees can access its computer system remotely from outside the firm (e.g. from home, from a hotel or while travelling).

The other four independent variables were measured through multiple items, since they are more complex and multi-dimensional by nature:

- The internal use of IS (INT_IS) was measured through six dichotomous (Yes/No) items. The first three of them INTIS1 to INTIS3 assess whether the firm uses an Intranet, an ERP and an accounting software respectively, while the other three items INTIS4 to INTIS6 assess whether the firm uses IS to share documents between colleagues or perform collaborative work in an online environment, to track working hours or production time, and to manage capacity or inventories respectively. The INT_IS variable was calculated as the average of these six items. The convergent validity of it (i.e. to what extent the above six items converge in measuring the same variable) was examined by performing principal components analysis (with varimax rotation) of these six items (according to the recommendations of the relevant statistical literature, such as Straub (2004)) using the SPSS 15.0 software; one component was formed (based on the criterion of eigenvalue >1), so we can conclude that this synthetic INT_IS variable has sufficient convergent validity. Also, the reliability of it was assessed by calculating the Cronbach Alpha of these six items using the SPSS 15.0 software; its value was 0.708 exceeding the recommended by the relevant literature minimum acceptable level of 0.7 (e.g. Straub, 2004), indicating that it is characterized by sufficient reliability.

- The extent of using IS for supporting cooperation with the external environment (EXT_IS) was measured through four dichotomous (Yes/No) items EXTIS1 to EXTIS4, which focus on firm's interaction with customers and prospects, and assess whether it uses IS for publishing offers to customers, answering calls for proposals or tenders, receiving orders from customers and enabling customers to pay online for ordered products or services respectively. The EXT_IS variable was calculated as the average of these four items. The convergent validity of it was examined by performing principal components analysis of these four items, which formed again one component, so we can conclude that EXT_IS variable is has sufficient convergent validity. Also, the Cronbach Alpha of these four items was 0.878, which exceeds the minimum acceptable level of 0.7, indicating its reliability.

- The impact of firm of ICT on firm's operations and performance (ICT_IMP) was measured through seven dichotomous (Yes/No) items ICTIMP1 to ICTIMP7, which assess whether ICT has a positive influence firm's revenue growth, efficiency of business processes, internal work organization, procurements cost, quality of products and services, quality of customer service and productivity respectively. The ICT_IMP variable was calculated as the average of these seven items. Similarly its convergent validity was examined by performing principal components analysis of the above seven items, which formed one component, indicating its convergent validity. Finally, the Cronbach Alpha of these seven items was 0.850, clearly exceeding the minimum acceptable level of 0.7, and therefore indicating its reliability.

- The innovation activity of firm (INNOV) was measured through four dichotomous (Yes/No) items INV1 to INV4. Two of them assess whether the firm has during the past 12 months launched any new or substantially improved products/services, or introduced any new or significantly improved internal processes; the other two assess whether the firm has introduced any ICT-based products/services or process innovations in the same period. The INNOV variable was calculated as the average of these four items. The convergent validity of it was examined by performing principal components analysis of these four items, which formed one component, so it can be concluded that INNOV variable is has sufficient convergent validity. Finally, the Cronbach Alpha of these four items was 0.792, exceeding the level of 0.7, and confirming its reliability.

Finally, the discriminant validity of the above four multiple-item variables was examined by conducting a principal components analysis of the 21 items of them. The results indicate that four factors are formed (with eigenvalues exceeding 1.0); each of them has high loadings (>0.5) of the items corresponding to one of the above variables, and much lower loadings of all the other items. Thus, the discriminant validity of the above four variables is confirmed.

4. RESULTS

Initially descriptive statistics of all the above items were calculated, which are shown below in Table 1 (for all items we can see the relative frequency of the positive response (Yes)). We remark that only 20.8% of the sample firms have adopted PKI, confirming that there has been a slow pace of adoption of this technology as mentioned in the introduction. Higher has been the adoption of telework through remote access to firm's computer system (35.1%). With respect to the examined internal IS types, we remark that the accounting software has the higher adoption (51.2%), followed by the Intranet (37.8%). On the contrary, much lower has been the use of ICT for supporting cooperation with customers or prospects (e.g. only 10% of sample firms use ICT to receive orders from customers). With respect to innovation, a considerable proportion of sample firms (40.3%) have introduced new or substantially improved products/services in the past 12 months, while a smaller proportion (33.4%) have introduced new or significantly improved internal processes. Finally, the majority of sample firms perceive a positive influence of their ICT infrastructure on business process efficiency (62.5%), internal work organization (60.1%), productivity (57.7%) and customer service quality (56.8%).

Item	Relative Frequency of positive response (Yes)
PKIAD: adoption of PKI	20.8%
TELEW: firm employees remote access to its computer system	35.1%
INTIS1: use of Intranet	37.8%
INTIS2: use of ERP	21.6%
INTIS3: use of accounting software	51.2%
INTIS4: use ICT to share documents or perform collaborative work	27.4%
INTIS5: use ICT to track working hours or production time	18.3%
INTIS6: use ICT to manage capacity or inventories	21.2%
EXTIS1: use ICT to publish offers to customers	10.1%
EXTIS2: use ICT to answer calls for proposals or tenders	9%
EXTIS3: use ICT to receive orders from customers	10%
EXTIS4: use ICT to enable customers to pay online for ordered products or services	5.1%
ICTIMP1: positive influence of ICT on revenue growth	48.1%
ICTIMP2: positive influence of ICT on business process efficiency	62.5%
ICTIMP3: positive influence of ICT on internal work organization	60.1%
ICTIMP4: positive influence of ICT on procurement cost	41%
ICTIMP5: positive influence of ICT on products/services quality	41.6%

ICTIMP6: positive influence of ICT on customer service quality	56.8%
ICTIMP7: positive influence of ICT on productivity	57.7%
INV1: new or substantially improved products/services	40.3%
INV2: ICT-based product/service innovations	21.5%
INV3: new or significantly improved internal processes	33.4%
INV4: ICT-based process innovations	23.9%

Table 1. Relative frequencies of positive responses to the dichotomous items

Next the regression model of equation 4.1 was estimated using LOGIT estimation, which is the recommended technique by the econometric literature if the dependent variable is dichotomous (e.g. see Gujarati and Porter (2009)). In addition to the six independent variables mentioned in sections 2 and 3 we have also included a sector control variable MANSERV taking value 0 for manufacturing firms and 1 for service ones. We can see the results in Table 2; for each independent variable is shown both b coefficient and also exp(b), which is equal to the increase of the odds ratio of the dependent variable (PKI adoption) if the corresponding independent variable increases by one unit; this allows comparison among independent variables as to their impact on the dependent variable.

We remark that all six independent variables have a positive statistically significant impact on PKI adoption, so all our six research hypotheses H1 to H6 are supported. This indicates that firm's size (measured through number of employees), adoption of telework, use of IS for supporting internal functions and cooperation with external environment, dependence of firm on its ICT infrastructure and propensity to innovation have a positive impact on PKI adoption. Also, we found that manufacturing firms have a greater propensity to adopt PKI. Since there is no particular characteristic of PKI that would make it more attractive to manufacturing firms we leave the interpretation of this trend for further research.

Independent Variable	**b**	**Stand. error**	**Signif.**	**exp(b)**
Ln(EMPL)	0.128	0.14	0.000	1.136
TELEW	0.531	0.048	0.000	1.700
INT_IS	0.941	0.099	0.000	2.562
EXT_IS	0.425	0.085	0.000	1.529
ICT_IMP	0.438	0.073	0.000	1.550
INNOV	0.479	0.067	0.000	1.615
MANSERV	-0.130	0.047	0.005	0.878
Constant	-2.346	0.050	0.000	0.096
N = 14065 Nagelkerke R Square = 0.134				

Table 2. The estimated PKI adoption regression model

Taking into account that five of our independent variables take values between 0 and 1

(TELEW, INT_IS, EXT_IS, ICT_IMP, INNOV), and the EMPL variable has been log-transformed, we can use the last column of Table 2 showing exp(b) for comparisons among these six independent variables as to their impact on PKI adoption. We can see that INT_IS is characterized by the highest exp(b) value (2.562) and therefore the highest impact, which means that the use of several diverse IS for supporting firm's internal functions poses significant challenges with regard to the management of authentication and authorization of users in different system domains, so it is a strong driver of PKI adoption. It is followed by TELEW (1.700), which means that in firms having employees working from remote locations (e.g. from home, from a hotel or while travelling) the need for reliable authentication increases, so they have a strong motivation to use PKI. Then follows INNOV (1.615), which means that firms having innovation tradition and culture have a stronger propensity to adopt the innovation that PKI brings in their processes. Furthermore, it should be noted that the impact of firm size, measured by the number of employees (EMPL), is strong as well, taking into account the corresponding exp(b) value (1.136) for the log-transformed variable. Therefore larger firms, having on one hand easier access to the required financial resources and technical expertise, and on the other hand more needs for effective and efficient user authentication and access control (which increase with the number of users), have a stronger propensity to adopt PKI.

5. CONCLUSIONS AND FURTHER RESEARCH

In this paper we have investigated the paradox of PKI (non-)adoption. PKI is an established technology that can offer a wide-range of security services, but it seems that most firms are reluctant to implement it. Current literature provides several possible explanations based on a theoretical analysis of PKI technology. We have analyzed actual survey data aiming to identify those factors that affect the adoption, or non-adoption, of PKI.

Our analysis indicates that PKI is not suitable for all kinds of firms and organizations. The resources needed for the implementation and management of PKI systems discourage SMEs; therefore, large firms are more likely to incorporate PKI in their systems. The number of system users is a decisive factor, as PKI provides a solution for controlling system access of large numbers of users. It is, also, useful for access control in systems with remote users. Consequently, firms that encourage tele-working are more likely to implement PKI systems.

An interesting result is that although PKI is an established, fifteen year old technology it is still regarded as innovative. As a result, it is mostly firms that have a culture of innovation that adopt PKI. In our opinion, PKI initiatives should focus on showing that it is not an experimental technology, any more, and there is little risk in applying it.

PKI, as most security technologies, are mainly implemented by firms that perceive a dependency on information systems, both internal and external. This result comes to corroborate the belief that management understands security in terms of fear (i.e., as a means of preventing unpleasant events) and not as a productivity enhancing tool.

In this research we have investigated only a fraction of the possible factors that affect PKI adoption with a focus on organizational characteristics. Several more factors should be investigated in the future. Particularly factors concerning the nature and characteristics of PKI technology. Moreover, our analysis was limited to the European region. World-wide surveys would have been very important for the PKI community.

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Appendix

Survey questions used in this study

Variable	Items
PKIAD	Do you use PKI? (Yes/No)
EMPL	How many employees does your company have?
TELEW	Can firm employees access its computer system remotely from outside the firm, for instance from home, from a hotel or while travelling? (Yes/No)
INT_IS	INTIS1: Do you use an Intranet?
	INTIS2: Do you use an ERP system (that is Enterprise Resource Planning System)?
	INTIS3: Do you use accounting software (other than a spreadsheet)?

	Does your company use online applications other than e-mail, for example a special software, to support any of the following business functions: Do you use online applications other than e-mail … [item]?
	INTIS4: to share documents between colleagues or to perform collaborative work in an online environment
	INTIS5: to track working hours or production time
	INTIS6: to manage capacity or inventories?
EXT_IS	Which of the following marketing or sales related processes does your company support by specific IT solutions? Do you use IT solutions for ... [item]?
	EXTIS1: Publishing offers to customers
	EXTIS2: Answering calls for proposals or tenders
	EXTIS3: Receiving orders from customers
	EXTIS4: Enabling customers to pay online for ordered products or services
ICT_IMP	All in all, in what ways have information and communication technologies influenced the business of your company? Please tell us for each of the following areas whether ICT has had a positive influence, a negative influence, or no influence at all. Would you say the influence of ICT on … [item] was …?
	ICTIMP1: revenue growth
	ICTIMP2: the efficiency of business processes
	ICTIMP3: internal work organization
	ICTIMP4: procurements cost
	ICTIMP5: quality of products and services
	ICTIMP6: quality of customer service
	ICTIMP7: the productivity of your company
INNOV	INV1: During the past 12 months, has your company launched any new or substantially improved products or services?
	INV2: Have any of these product or service innovations been directly related to or enabled by information or communication technology?
	INV3: During the past 12 months, has your company introduced any new or significantly improved internal processes, for example for producing or supplying goods and services?
	INV4: Have any of these process innovations been directly related to or enabled by information or communication technology?