The Distinct Effects of Information Technology and Communication Technology on Firm Organization

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Abstract

Empirical studies on information communication technologies (ICT) typically aggregate the 'information' and 'communication' components together. We show theoretically and empirically that this is problematic. Information and communication technologies have very different effects on the decisions taken at each level of an organization. Better information access pushes decisions down, as it allows for superior decentralized decision making without an undue cognitive burden on those lower in the hierarchy. Better communication pushes decisions up, as it allows employees to rely on those above them in the hierarchy to make decisions. Using an original dataset of firms from the US and seven European countries we study the impact of ICT on worker autonomy, plant manager autonomy and span of control. Consistently with the theory we find that better information technologies (Enterprise Resource Planning, ERP, for plant managers and CAD/CAM for production workers) are associated with more autonomy and a wider span of control. By contrast, communication technologies (like data networks) decrease autonomy for both workers and plant managers. Treating technology as endogenous using instrumental variables (distance from the birthplace of ERP and heterogeneous telecommunication costs arising from different regulatory regimes) strengthen our results.

JEL No. O31, O32, O33, F23

Keywords: organization, delegation, information technology, communication technology, the theory of the firm.

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1 Introduction

Most studies of the impact of information and communication technologies (ICT) on firm organization, inequality and productivity (see below) treat ICT as an aggregate homogeneous capital stock. However, these technologies have at least two distinct components. First, through the spread of cheap storage and processing of data, information stored in databases is becoming cheaper to access. Second, through the spread of cheap wired and wireless communications, agents find it easier to communicate with each other (e.g. e-mail and mobile devices). Reductions in the cost of accessing information stored in databases and of communicating information among agents can be expected to have a very different impact on firm organization. While cheaper communication technology facilitates specialization, generating a reduction in the variety of tasks performed by workers as agents rely more on others, cheaper information access has an 'empowering' effect, allowing agents to handle more of the problems they face without relying on others. This difference matters not just for firms' organization and productivity, but also in the labor market, as information access and communication technology changes can be expected to affect the wage distribution in opposite directions.[1] In this paper, we utilize a new international firm-level data set with directly measured indicators of organization and technologies to study whether indeed ICTs have these distinct effects.

Our starting point is the analysis in Garicano (2000) on the hierarchical organization of expertise. Decisions involve solving problems and thus acquiring the relevant knowledge for the decision. In determining at what hierarchical level decisions should be made, firms face a trade-off between *information acquisition costs* and *communication costs*. Making decisions at lower levels implies increasing the cognitive burden of agents at those levels. For example, decentralizing from the corporate head quarters (CHQ) to plant managers over the decision whether to invest in new equipment requires training plant managers to better understand financial decision making, cash flows, etc. To the extent that acquiring this knowledge is expensive, the knowledge of the plant manager can be substituted for by the knowledge of those at corporate head quarters. Relying more on the direction of corporate head quarters reduces the cognitive burden on the plant manager and so lowers the total information acquisition costs. But this comes at the price of increasing communication between levels in the hierarchy, increasing total communication costs. From a cognitive perspective, decentralized decision making thus implies an increase in the cost of information acquisition to economize

[1] For example, Garicano and Rossi-Hansberg (2006) analyze theoretically this impact on wages.

on communication costs: trading-off knowing versus asking for directions.

The level at which decisions are taken thus responds to the cost of acquiring and communicating information. Reductions in the cost of communication allows for a reduction in knowledge acquisition costs through the increasing use of 'management by exception', e.g. local managers rely more on corporate managers for decision making. Reductions in the cost of information access, on the other hand, reduce the cognitive burden imposed by decentralized decision making and makes more decentralization efficient. Consequently, information and communication technologies affect differently the hierarchical level at which different decisions are taken. Improvements in information technology should push decisions 'down' leading to decentralization while improvements in communication technology should push decisions 'up' leading to centralization.

In this paper, we study this cognitive view of hierarchy by testing for the differential impact on the organization of firms of these two types of technologies (information vs. communication). To do this, we extend Garicano (2000) to consider two types of decisions and discuss in each case technologies that make it easier for agents to acquire the information necessary to make them and their technologies that improve communication. This extension is methodologically important as the data available to researchers on real authority has multiple types of decisions (e.g. worker decisions on the production line vs. managerial decisions on investment). First, we consider *non-production decisions*. These decisions can either be taken at the central head quarters by corporate officers, or delegated to a business unit (in our case, the plant manager). The specific decisions that we study are capital investment, hiring new employees, new product introductions and sales and marketing decisions. The key piece of information technology that has recently affected information access by these managers is, as we discuss in Section 3, Enterprise Resource Planning (ERP). These ERP systems increase dramatically the availability of information to decision makers in the company, that is they reduce the cost of acquiring information to solve a problem[2]. It follows that they should increase the autonomy of the plant manager.

Second, we consider factory floor *production decisions*. These are decisions on the production process that can either be taken by factory floor employees or by those in the plant hierarchy, such as which tasks to undertake and how to pace them. Here, a key technological change in the manufacturing sectors we focus on is the introduction of Computer Assisted Design/Computer Assisted Manufacturing (CAD/CAM). A worker with access to those ma-

[2] We present survey evidence consistent with our discussions with technology experts that ERP primarily reduces information acquisition costs rather than reducing communication costs.

chines can solve problems better, and thus needs less access to his superiors in making decisions. This technology should increase their autonomy and, by reducing the amount of help they need from plant managers, increase the span of control of plant managers.

In sum, we expect 'information technologies' (ERP and CAD/CAM) to decentralize decision making respectively in non production decisions (from CHQ to plant managers) and in production decisions (from plant managers towards production workers). On the other hand, as we argued above, we expect communication technologies to centralize decision making. This will be true both for production workers (so that plant-managers will take more of their decisions), and also for plant-managers (so that the central head quarters will take more of their decisions). A key technological innovation affecting communication is the growth of networks. We thus also test whether the availability of networks reduced the decision making autonomy in production decisions of workers, and in non-production decisions of managers.

We utilize a new data set that combines plant-level measures of organization and ICT across the US and Europe. The organizational questions were collected as part of our own management survey work (see Bloom and Van Reenen, 2007) and were asked to be directly applicable to the theories we investigate. The technology dataset is from a private sector data source (Harte-Hanks) that has been used mainly to measure hardware utilization in large publicly listed firms (e.g. Bresnahan, Brynjolfsson and Hitt, 2002), whereas we focus on the less used software components of the survey.

In terms of identification, we mainly focus on conditional correlations between the different ICT measures and three dimensions of the organization of the firm, guided by our theoretical predictions. But we also consider two instrumental variable strategies. First, we use the distance from the birthplace of SAP, the first major ERP (and still the market leader) as an instrument for ERP presence, drawing on the general observation (which is true in our data) that the diffusion of an innovation generally has a strong geographical dimension.[3] Second, we utilize the fact that the differential regulation of the telecommunication industry across countries generates exogenous differences in the effective prices of networks. We show that industries that exogenously rely more on networks are at a greater disadvantage in countries with high communication costs, and use this to identify the effect of communication costs on decentralization. Our IV results support a causal interpretation of the effect of information and communication technologies on firm organizational.

[3] Examples of how geographical proximity is important for diffusion include Holmes (2010), Griffith, Lee and Van Reenen (2007), Skinner and Staiger (2005), Henderson, Jaffe and Trajtenberg (2003) and (for a survey) Foster and Rosenzweig (2010). Becker and Woessmann (2009) use distance from Wittenberg as in instrument for the spread of Protestantism in Germany which they show fosters human capital. Note that in our regressions we control for human capital, so this cannot be driving the results.

In short, the evidence is supportive of the theory. Technologies that lead to falling information costs for non-production decisions (like ERP) tend to empower plant managers (relative to the CHQ) and technologies that lead to falling information costs for production decisions (like CAD/CAM) tend to empower workers relative to plant managers. Information technologies also widen the span of control. By contrast, technologies that reduce communication costs (like networks) lead to more centralization and have ambiguous effects on the span of control (in the theory and the data).

As we argued above, much previous empirical work on has tended to aggregate ICTs together as one homogenous technology due to data constraints, often simply measured by computers per person or "ICT capital". As noted above, this is problematic since hardware will simultaneously reduce information and communication costs, and we show that these should have very different effects on firm organization. One strand of the literature looks for complementarities between ICT and organizational aspects of the firm, but takes organization as exogenous.[4] A second branch tries to endogenize organization, but does not discriminate between types of ICT.[5] A third branch, which we are perhaps closest to, looks more closely at the effects of ICT on organization but does so in the context of a single industry in a single country.[6] What is unique about our study is the disaggregation of types of ICT and organization across a number of industries and countries.

An alternative to our cognitive perspective is that hierarchies may be a solution to incentive problems (e.g. Calvo and Weillisz, 1978; Aghion and Tirole, 1997; Dessein, 2002), linked to automation (Autor et al, 2003) or the result of coordination issues (Cremer et al. 2007 and Alonso et al, 2008). Although we do not reject the potential importance of other mechanisms, we think our information perspective is first order and provide some empirical support for this in a range of robustness tests.[7]

We proceed as follows. In Section 2 we discuss a basic theoretical framework that allows us to study the impact of information and communication technologies. We then map the model to the data by identifying some key factors that affected information and communication costs (Section 3). We then discuss our data (Section 4), and present our results (Section 5). The

[4] See the survey in Draca, Sadun and Van Reenen (2007). Examples include Bartel, Ichinowski and Shaw (2007), Black and Lynch (2001), Bloom, Sadun and Van Reenen (2007) and Bresnahan, Brynjolsson and Hitt (2002).

[5] For example see Acemoglu et al (2007), Caroli and Van Reenen (2001), Colombo and Delmastro (2004), Crepon et al (2004) and Aubert et al (2004). To explain the evidence for trend delayering described in Rajan and Wulf (2006), Guadalupe and Wulf (2008) emphasis competition rather than ICT.

[6] See, for example, Baker and Hubbard (2003, 2004) or the case studies in Blanchard (2004).

[7] Our work also relates to the wider theoretical literature on firm delegation. For example, see Baron and Besanko (1992), Melumad et al (1995), Mookherjee (2006), Baker et al (1999), Radner (1993) and Hart and Moore (2005).

final section offers some concluding comments.

2 Theory

2.1 Communication technology Centralizes; Information Technology Decentralizes

Garicano (2000) proposes a theory of a hierarchy as a cognitive device. In the model the role of hierarchy is to facilitate the acquisition of knowledge by increasing its utilization rate. Here we present a simplified version of that theory, which allows us to extend it towards a setting with different types of decisions (production and non-production).

Assumption 1. Production requires time and knowledge. Each production worker draws a unit measure of problems (or tasks or decisions) in $[0, 1]$ per unit of time. Production only takes place if all the problems are dealt with by someone in the organization. We normalize to 1 the output per agent and per unit of time once problems are solved. Some problems occur more often than others: problems are distributed according to a density function $f(z)$. Agents can only deal with a problem or task if they have the relevant knowledge.

Assumption 2. Knowledge acquisition is costly. The cost incurred by an agent i to acquire the knowledge necessary to deal with all problems is a_i. This cost may depend on the technology available to different agents and their skill. Thus an agent who acquires the information required to perform all the tasks produces net output $1 - a_i$.[8]

Assumption 3. Knowledge can be communicated. The cost of training agents can be reduced through a hierarchy in which production agents' autonomy is reduced, so that they only need enough knowledge to deal with some problems - that is, those in $(0, z_p)$- and ask for help on the rest to an agent who is specialized in problem solving, whose knowledge we call z_m(m for manager). The communication or helping cost h is incurred whenever help is sought, that is h is incurred per question posed. Clearly, communication is minimized if workers learn the most common problems and ask help on the rest; thus without loss of generality, we reorder problems so that $f'(z) < 0$, i.e. more common problems have a lower index and are performed by workers. That is 'management by exception' is optimal, where workers do routine tasks and managers deal with the exceptions.[9] Figure 1 illustrates this task allocation.

[8] The cost of information acquisition was denoted "c" in earlier versions to be consistent with Garicano (2000). The change in notation was made to avoid confusion with communication, or helping, cost "h".We assume the cost of learning is linear so that learning z problems costs az. This is without loss, as we can redefine problems of tasks so that $f(z)$ is the frequency of a renormalized (equal cost) problem.

[9] See Garicano (2000) for a formal proof and characterization of this result. In that paper, there are potentially many layers of problem solvers, and organizations can decide which problems to do and which ones not to deal

[Figure 1 about here]

The value of the additional layer of problem solvers is that by reducing lower level workers' decision range, the cost of acquiring information is reduced. The cost of hierarchy is the time wasted in communication, since problem solvers do not produce output, but instead use their time to help others solve their problems.

Suppose a team must deal with N problems per unit of time. The team needs then N production workers in layer 0 and n_m managers or problem solvers. The profits generated by this hierarchy with N production workers, each receiving a wage w_p, and n_m managers specialized in 'problem solving' or 'helping', receiving a wage w_m, is:[10]

$$\pi = N - N(a_p z_p + w_p) - n_m(a_m z_m + w_m) \tag{1}$$

that is, when the N production workers have autonomy z_p they must learn the z_p most common problems. We further assume (although it is unnecessary for the results) that the learning technology is such that managers know all the tasks that workers also know, and more, so that knowledge overlaps.[11] Thus since all tasks must be dealt with $z_m = 1$. A production agent can deal with a fraction $F(z_p)$ of the tasks and asks for help with probability $(1 - F(z_p))$. Thus a manager spends time $h(1 - F(z_p))$ helping each production worker. Since there are N agents, the needed number of managers or problem solvers is $Nh(1-F(z_p)) = n_m$, resulting in a span, or ratio of workers per manager of $s = N/n_m$. This constraint determines a trade-off between what the agents below can do and how many managers are needed. The more knowledge acquired by lower level agents, the less managers are needed. Figure 2 provides an overview of the model.

The problem of the hierarchy is to decide the size or span of the hierarchy (s) and the degree of worker autonomy (z_p) so as to maximize profits per problem. Substituting for n_m in equation (1) we obtain:

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with at all- while here all problems must be solved. It is shown that the organization set up in the model (characterized by 'management by exception') is optimal. Intuitively, if those lower in the hierarchy learnt exceptions (rather than routine tasks), the tasks could be swapped, reducing communication costs. Here, in our basic model, there are only two layers and all problems are (eventually) solved; the only choice is who learns the solution. The model with two types of problems in Section 3.2. extends the framework in Garicano (2000).

[10] We are solving throughout for the partial equilibrium effects (taking wages as given) as is common in the literature (see e.g. Milgrom and Roberts, 1990). For a general equilibrium analysis with heterogeneous workers (i.e. where wages are adjusting) see Garicano and Rossi-Hansberg (2006).

[11] This overlapping knowledge assumption is used because it seems more reasonable in the empirical context, but it is irrelevant for the comparative statics in the propositions here, as can be seen by replacing $h(1 - F(z_p))(a_m + w_m)$ by $h(1 - F(z_p))(a_m(1 - z_p) + w_m)$. Overlapping knoweldge could result from learning that takes place on the job or because the process of learning involves learning the 'easy' tasks first.

$$\pi^* = \max_{z_p}[N\left(1 - \left(a_p z_p + w_p\right) - h(1 - F(z_p))\left(a_m + w_m\right)\right)]$$

[Figure 2 about here]

The following comparative statics follow immediately.

Proposition 1 ***Communication Centralizes; Information Access Decentralizes***

1. *A drop in communication (or 'helping') costs (h) reduces worker autonomy (z_p) and has an ambiguous impact on span of control $s = N/n_m$ (more questions are asked, but each one takes less time).*

2. *A reduction in the cost of acquiring information of all agents ($a = a_m = a_p$), or one affecting only lower level agents, a_p, increases lower level autonomy (z_p) and increases managerial span of control, s (as less questions are asked).*

The formal proof of the above is straightforward. Note first that $f'(z) < 0$ implies that the second order conditions for optimization is met, $\partial^2\pi/\partial z_p^2 < 0$. Then the first result follows from the fact that $\frac{\partial^2\pi}{\partial z_p \partial h} > 0$. Second, letting $a_p = a_m = a$, we have that at the optimum (using the first order conditions): $\frac{\partial^2\pi}{\partial z_p \partial a} < 0$. Similarly $\frac{\partial^2\pi}{\partial z_p \partial a_p} < 0$, i.e. if workers can learn cheaper they do more.. The changes in span follow straightforwardly from $s = N/n_m = 1/\left(h(1 - F(z_p))\right)$.

The intuition for these results is as follows. (1) Higher communication cost raises the value of additional worker knowledge, since that economizes on communication. (2) Higher information acquisition costs for all agents raise the value of asking questions for workers, economizing on expensive information acquisition. Essentially, while communication cost reductions facilitate the reliance of specialist problem solvers and decrease what each worker can do, reductions in the cost of acquiring information make learning cheaper and reduce the need to rely on specialized problem solvers for help with solutions.

2.2 Extension: Production and Non Production Decisions

Middle managers perform two broadly different functions. First, they are at the top of the production hierarchies, dealing with the problems that production workers could not handle, as outlined in the model above. Second, they also are at the bottom of a non-production hierarchy, potentially dealing with managerial decisions on things like hiring/firing, investment, product introduction and marketing delegated to them by central head quarters. To study the implications of the multiple roles played by middle managers, we extend the model in the

simplest possible way considering a multilayer hierarchy involving corporate managers, middle managers (in our data, plant managers) and production workers.

In this extension, corporate head quarters and middle-managers deal with non-production (management) decisions, x, while middle-managers and production workers deal with production decisions, z.

Production Decisions: As above, each production worker confronts one production decision per unit of time, $z \in [0,1]$. He can deal with a measure z_p of these production decisions. That is, for those $z > z_p$, he asks a middle manager for help. Decisions are distributed according to cdf $F(z_p)$, with pdf $f(z_p)$. As previously, optimality (management by exception) implies $f'(z_p) < 0$, so that production workers specialize in the more common tasks. A cost h is incurred each time the middle manager must be involved in production. Production workers can acquire knowledge at cost a_p and middle managers at cost a_m. A firm that must deal with N production problems requires, as previously, $h(1 - F(z_p))\, N = n_m$ middle managers.

Non-Production Decisions: The existence of a hierarchy generates non-production decisions. In particular, each middle manager generates a measure 1 of non-production decisions per unit of time, where non-production decisions $x \in [0,1]$, are drawn from a density function $g(x)$, again with $g'(x) < 0$ implied by optimality. If the middle manager has the knowledge to deal with these decisions, he does so instantaneously. If he does not, he passes on the problem to corporate head quarters. Similarly to production workers, middle managers acquire knowledge so that they can take a fraction x_m of those decisions (they can solve those problems). Thus if the problem drawn is $x < x_m$, a middle manager solves it; if not, the corporate manager intervenes. A helping cost h is incurred as before when top managers have to intervene, that is helping each middle manager costs $(1 - G(x_m))h$ units of corporate manager's time.[12] For an agent i to learn to take (all) of the non-production problems costs a_i, a cost dependent on the technology available to manager i; thus training middle managers to deal with non production problems costs $a_m x_m$, while, analogously to the production decision case, corporate managers can deal with all (a unit measure) of non-production problems at a cost a_c (c for corporate), with $a_c \gtrless a_m$. A hierarchy with n_m non-production problems where middle managers have knowledge x_m requires $(1 - G(x_m))hn_m = n_c$ corporate managers.

Thus the profits of a hierarchy with production workers, middle managers and corporate managers are given by:

[12] We assume communication or helping cost h is the same for production and non-production decisions for simplicity since in our empirical application we cannot distinguish different communication costs. Conceivably, some technologies may affect communication costs differently for production and non-production, and that would have to be taken into account in the formulation.

$$\pi^* = \max_{z_p, x_m, n_m, n_c} N - (a_p z_p + w_p)N - (a_m + a_m x_m + w_m)n_m - (a_c + w_c)n_c \quad (2)$$

The first term are the N units of output produced by N production workers. The second term is the costs of employing production workers - their wage (w_p) and the costs of providing them with enough information to deal with decisions $z < z_p$ ($a_p z_p$). The third term is the cost of n_m middle managers - their wage (w_m), and training them to deal with production problems (a_m) and with a fraction x_m of non-production problems. The cost of dealing with production and non-production problems is assumed to be the same, since a given technology is available to each manager to deal with these problems[13]. The last term is the cost of n_c corporate managers - their wage (w_c) and training them to deal with a measure of 1 non-production problems (a_c). The organization must choose the set of decisions dealt with by workers and middle managers, z_p and x_m (as illustrated graphically in Figure 3), as well as the number of middle managers and corporate managers, subject to the time constraints of middle managers and corporate managers.

[Figure 3 about here]

Replacing the number of middle managers n_m and of corporate managers n_c required to manage N production workers, the profits per production worker can be written (dividing equation (2) through by N, and noting that the profit function is constant returns to scale in N):

$$\frac{\pi^*}{N} = \max_{z_p, x_m} 1 - (a_p z_p + w_p) - (a_m + a_m x_m + w_m)h(1 - F(z_p)) - (a_c + w_c)h^2(1 - F(z_p))(1 - G(x_m)) \quad (3)$$

Which allows us to generalize in a straightforward manner the results above.

Proposition 2 *1. A reduction in communications costs (h) leads to a reduction in production decision making by production workers (z_p) and in non-production decision making of middle managers (x_m), and has an ambiguous impact on spans of control.*

2. A reduction in the cost of acquiring information of lower level agents (a_p) leads to an increase in production workers autonomy (z_p) and in the span of control of middle managers ($s_m = N/n_m$).

[13] This assumption can be weakened by assuming them different, with the only cost being the extra notation.

3. *A reduction in the cost of acquiring information either by middle managers (a_m) or by them and corporate managers (a_c and a_m) increases autonomy of middle managers in non-production decisions (x_m), and the span of corporate managers ($s_c = n_m/n_c$); it reduces the autonomy of production workers (z_p), and the span of control of middle managers (s_m).*

We show these results formally in Appendix A.

In summary, the framework generates eight comparative static results for the direct impact of the information cost and technology cost variables (a_p, a_m, h) on the four organizational outcomes (x_m, z_p, s_m, s_c) shown in propositions 1 and 2. We report tests of six of these predictions for worker autonomy, plant manager autonomy and plant manager (x_m, z_p, s_m) in the main paper, as we have good measures of these organizational variables. We report results for the remaining two predictions for CEO span (s_c) in the Appendix because unlike plan manager span we do not measure CEO span directly. From the theory there are also a further four "cross" predictions of the indirect effects of technology on organizational measures - such as the impact of production information costs on plant manager autonomy. We also report tests of these more subtle effects in the Appendix.

3 Changes in Information and Communication Technology

The model suggests that two key aspects of information and communication technology matter: the cost of information access and the cost of communication. In this section we introduce three technological changes that had impact on information and communication technology. Concerning communication (or 'helping') technology, we focus on the introduction of intranets ($NETWORK$). Concerning information access technology, we focus on the widespread adoption of CAD/CAM technologies, and the introduction of large, real time, connected databases, in the form most notably of 'enterprise resource planning' (ERP) systems. The reason we focus on these three technologies is that they are major advances in the manufacturing sector that we study, as well as other sectors like retail, wholesale and banking.[14] We also believe they map clearly into reductions in communication costs ($NETWORK$) and reductions in information acquisition costs for non-production decisions (ERP) and production decisions (CAD/CAM).

[14] This is based on reviewing the literature, US, UK, China and India factory visits and discussions with engineers and consultants at Sun Microsystems, EDS, HP, McKinsey and Accenture.

3.1 The Rise of Intranets: Facilitating Communication through the Organization (h)

A first parameter that affects the allocation of decisions in our model is communication costs. An important shifter of these costs over last decade has been the introduction of corporate intranets. These allow companies to connect all the plants to corporate head quarters, reducing the cost of communication between head quarters and local managers. In the past, for example, sharing documentation with head quarters required the use of fax or mail. These high communication costs made speedy decisions from the centre head quarters extremely difficult and costly, leading to the delegation of day-to-day control of the plant to local management. Once the leased-lines and corporate intranet are installed, the cost of communication between local and central managers is reduced. This allows for the use of more experienced central management to be swiftly alerted to signs of production problems - for example identifying specific types of output variations as fault indicators - and able to provide swift decision making support. Intranets also reduced the cost of communication inside the production plants, facilitating the flow of information between the shop floor and the plant manager. These network technologies are equally important in retail, wholesale and retail banking. Other general communication technologies include cell phones and e-mail.

Given the model, we expect the rise of intranets, which reduces communication cost, to be a *centralizing technology,* as it allows for 'questions' to be more cheaply posed to the experts.

3.2 Computer Assisted Design and Manufacturing (CAD/CAM): Increasing Information Access at the Shop Floor (a_p)

A second important parameter in our model is the change in information costs on the production floor. A crucial recent change in these costs has been the introduction of CAD/CAM.

New manufacturing orders generally require design, testing and redesign, typically by the engineering department. In the past, the process traditionally started with the design being provided by the supplier - for example an exhaust pipe for a new military vehicle - which the engineers would mock-up and produce in a trial run. Once this was successful the engineers would go to the manufacturing facility, e.g. the exhaust factory, to supervise a small scale production run, and produce the first prototypes. The local manager would oversee this process, working with the engineers to ensure his plant could implement the designs in-house, or have these externally procured. These initial production runs would then be shown to the customer, refined in a further design iteration, and finally set-up for the full-scale production run by the engineers. The introduction of CAD (computer aided design) allows the plant to directly de-

sign products, and CAM (computer automated manufacturing) enables the production team to program up the Computer Numerical Control equipment to produce the key parts.[15]

In this way, CAD/CAM has increased the amount of information available to the production team and enabled them to carry out the initial prototype design and production stage, reducing the involvement of both the plant manager and the remotely based central head quarters engineering team. Similar technologies in retail and banking, like customer databases and relationship management tools, have empowered store-level employees to cross-sell other products like insurance and credit (e.g. Hunter et al, 2001).

Given the theory described above, we expect CAD/CAM to be a *decentralizing technology*: since workers have access to more/better information, they can make more decisions themselves without consulting their superiors.

3.3 Connected Real Time Data Bases: Increasing Managerial Information Access (a_m, a_c)

The cost of access to information by local plant manager (a_m) and central (a_c) managers has been directly affected by the installation in firms of Enterprise Resource Planning (ERP) systems. ERP is the generic name for software systems that integrate several data sources and processes of an organization into a unified system. These applications are used to store, retrieve and share information on any aspect of the production and sales process in real time. This includes standard metrics like production, waste, deliveries, machine failures, orders and stocks, but also broader metrics on human resource and a range of financial variables. An ERP system is based on a common database and a modular software design. The main sellers of ERP are SAP and Oracle, both used by more than half of large US business. The introduction of ERP systems is typically the largest investment in information technology in manufacturing related business: in 2006, ERP was estimated to represent just under one third of all application IT spend in large US companies.[16]

To understand the impact of ERP consider again the example for an exhaust factory. After the introduction of SAP 5.0, such a production plant would have all its data collected and stored in one unified computing system, allowing the plant manager (and all other managers) to easily access and compare data across a range of processes. For example, if a filter supplier were to shut-down due to a fire, the plant manager could use his ERP system to generate

[15] Traditionally these would be used to drive numerically controlled programming tools (see for example, the description of their use in the valve industry in Bartel et al, 2007).

[16] These estimates are from Shepard and Klein, (2006) who conducted 175 interviews with IT managers in U.S. based companies with 1,000 or more employees. ERP systems are also increasingly common in larger firms in developing countries, see for example Bloom et al. (2010).

an on-line inventory of current filter stocks, a read-out of work-in-progress, and customer orders outstanding, to evaluate which customer orders were most at risk from shortages. This would enable him to re-schedule filter stocks towards the most imminent customer orders, and pause production of less imminent orders until alternative suppliers could be found. He would also able to call-up a list of alternative filters and their suppliers to source a replacement supplier. Once the local manufacturing sites and the company head quarters are integrated in the company-wide ERP system, plant managers and the central head quarters have a full company-level overview of production, inventory, orders and finance across the company. Therefore, the development of ERP enables managers to access timely information at an unprecedented rate, empowering plant managers to make decisions on a range of activities including investment, hiring, pricing and product choice[17].

Given the theory, we expect ERP to be a decentralizing technology: as all managers have better access to information, lower level managers can make more decisions without consulting their superiors. In the data section below we show that indeed, ERP increases information access by managers.

To sum up, three important technological changes that have been observed:

- A reduction in the cost of communicating information, particularly as a result of the growth in corporate intranets ($NETWORK$).
- An improvement in the access to information by production workers and shop floor workers as a result of CAD/CAM and customer databases
- An improvement in the access to information by all managers across the organization as a result of the introduction of ERP

We believe that these changes map directly to the theory. Table 1 considers the effects of reductions in communication and information costs on three organizational outcomes; plant manager autonomy in column (1); workers' autonomy in column (2); and plant manager's span in column (3). Falling communication costs (proxied by $NETWORK$) have negative effects on autonomy and ambiguous effects on spans (each worker does more but will ask more question). Falling information acquisition costs for non-production decisions (proxied by ERP) are instead predicted to raise autonomy for plant managers. Finally, falls in information acquisition costs for production decisions (proxied by CAD/CAM) are predicted to increase both worker autonomy and plant manager's span (they can manage more workers if these

[17] By improving the access of managers to local time information ERP also allows managers to make better decisions (see Davenport et al, 2002).

workers are making more of their own decisions). To reiterate, the intuition is as in the previous section: Better information access pushes decisions down, as it allows for superior decentralized decision making without an undue cognitive burden on those lower in the hierarchy. Better communication pushes decisions up, as it allows employees to rely on those further up the hierarchy to make decisions.

3.4 Alternative Theoretical Channels

We close this section with a brief discussion of alternative hypothesis through which ICTs could affect the allocation of decisions and span and how we might distinguish them from the cognitive approach we emphasis in this paper.

3.4.1 Agency and Incentives

It is difficult to have a general view of how technology affects agency without being precise about the channels. Specifically, would we expect delegation to increase or decrease as a consequence of ICT improvements? The key characteristic that will affect whether delegation should increase or decrease is the extent to which technical changes facilitate monitoring inputs or monitoring outputs. As Prendergast (2002) showed, a technology that results in better measures of output will increase delegation, as incentives can be used to align decision making. On the other hand, a technology that facilitates monitoring of inputs will reduce delegation. Specific technologies, and specific instances of the technology, may have stronger impact on inputs or on outputs. For example, Baker and Hubbard (2004) have argued that a specific piece of ICT, the on-board computers used in trucks, decrease the cost of monitoring a trucker's level of care in driving (an input). As a result, these on-board computers induced an increase in vertical integration (less incentives and delegation). The opposite prediction may be easily the consequence of a particular type of ICT. This may be particularly the case for ERP, which provides better information about agents' production decisions and so can facilitate delegation with monetary incentives.

Absent a specific technology like on board computers, we believe that there may be multiple channels through which the technologies that we examine may affect incentive conflicts. Rather than formulating a large range of hypothesis on incentives and decision making, we simply note that if technology affects output monitoring, it should also affect delegation and incentive payments. We can explicitly test whether this is driving our results by controlling in our regressions for the impact of ICT on delegation *holding incentives constant*. We perform this exercise in Table A6 by including measures of the importance of incentive pay, and we show

that our key results appear robust to this extension.

3.4.2 Automation

Autor, Levy and Murnane (2003) have argued that the key way ICT impacts the division of labor is through "automation". Essentially, their argument is that the routine tasks of both low human capital workers (like assembly line workers) and higher human capital workers (like bank clerks) have been replaced by computerization and do not have to be either learned or undertaken by workers or managers. In a bank, for example, information technology allows for automatic sorting of checks.

We can extend our model to deal with this type of mechanism. Specifically, suppose that a worker is in charge of tasks z_0, the machine is in charge of tasks m and the manager of tasks $1 - z_0 - m$. The impact of automation is to increase the number of tasks m undertaken by the machine. Straightforward comparative statics show that the number of tasks undertaken by a worker is reduced, as the machine does the more routine tasks. Thus a worker does $z_0 - m$ tasks compared to z_0 tasks before, while the manager continues to do $1 - z_0$ tasks, thereby reducing the share of tasks carried out by worker. The reason is that the marginal value of learning an additional task does not get increased by the machine doing the most routine task, so z_0 stays constant. The span of control remains unchanged as the number of tasks done by the manager $1 - z_0$ are unchanged.

Our data allows testing of this channel since, if any of our ICT measures is having an impact through automation, then this will reduce the number of tasks done by lower level agents, reducing their autonomy. By contrast, our perspective predicts increases in the number of tasks done by lower level agents in response to falls in information acquisition costs. Another distinguishing feature of our theory is that we obtain specific predictions on the impact of networks, which the automation perspective is largely silent on.

3.4.3 Coordination

One key aspect of *ERP* is that, in unifying multiple previously unrelated databases, it facilitates coordination between previously independently operated business units. In fact, by creating a common language, *ERP* facilitates the substitution of 'hierarchical' communication by 'horizontal' or peer-to-peer communication, as Cremer, Garicano and Prat (2007) have noted. As a result, if coordination across units is becoming easier and less hierarchical, we could also expect (similarly to the effect we predict in our theory) ERP to result in 'empowerment,' as managers of previously existing business units coordinate with those of others

without going through central management. This could also complement changes in incentives towards horizontal communication, as in an Alonso et al. (2008) type model.

The pure coordination story where the main impact of the information and communication changes is to decrease coordination costs, however, will be easy to tell apart from ours. First, coordination theories do not have implications for spans of control. In fact, if horizontal communication increases, we will see an increase in the amount of coordination that takes place, and that could lead to a bigger role for managers and a smaller span when ERP is introduced (contrary to our hypothesis). Second, if the changes in communication costs also act through the coordination channel, they should also result in decentralization, rather then centralization.

In other words, the coordination perspective does not result in a sharp distinction between information costs (ERP and CAD/CAM) and communication costs ($NETWORK$). Both reduce coordination costs, and thus result in the same impact on decentralization (larger) and on spans (ambiguous). The data will allow us to differentiate this perspective from ours, since we expect changes in information and communication costs to have different organizational outcomes.

4 Data

We use a new international micro dataset combining novel sources from the US and several European countries. Our two main sources of data are the Center for Economic Performance (CEP) management and organization survey and the Harte-Hanks ICT panel. We also match in information from various external data sources such as firm-level accounting data, industry and macro-economic data.

4.1 The CEP management and organization survey

4.1.1 Overview

In the summer of 2006 a team of 51 interviewers ran a management and organizational practices survey from the CEP (at the London School of Economics) covering over 4,000 firms across Europe, the US and Asia. In this paper we use data on approximately 1,000 firms from the US, France, Germany, Italy, Poland, Portugal, Sweden and the UK for which we were able to match the organization data with ICT data from an independent database. Appendix C provides detailed information on our sources, but we summarize relevant details here.

The CEP survey uses the "double-blind" technique developed in Bloom and Van Reenen (2007) to try and obtain unbiased accurate responses to the survey questions. One part of

this double-blind methodology is that managers were not told they were being scored in any way during the telephone survey. The other part of the double blind methodology is that the interviewers knew nothing about the performance of the firm as they were not given any information except the name of the company and a telephone number. Since these firms are medium sized, large household names are not included.

The survey is targeted at plant managers in firms randomly drawn from the population of all publicly listed and private firms in the manufacturing sector with between 100 and 5,000 employees. We had a response rate of 45% which was uncorrelated with firm profitability or productivity. The interviews took an average of 45 minutes with the interviewers running an average of 78 interviews each, over a median of 3 countries, allowing us to remove interviewer fixed effects. We also collected detailed information on the interview process, including the interview duration, date, time of day, day of the week, and analyst-assessed reliability score, plus information on the interviewees' tenure in the company, tenure in the post, seniority and gender. We generally include these variables plus interviewer fixed-effects as 'noise-controls' to help control for any potential measurement error.

4.1.2 Measuring Plant Manager Autonomy

As part of this survey we asked four questions on plant manager autonomy. First, we asked how much capital investment a plant manager could undertake without prior authorization from the central head quarters. This is a continuous variable enumerated in national currency (which we convert into US dollars using Purchasing Power Parities). We also asked where decisions were effectively made in three other dimensions: (a) hiring a new full-time permanent shopfloor employee, (b) the introduction of a new product and (c) sales and marketing decisions. These more qualitative variables were scaled from a score of one, defined as all decisions taken at the corporate head quarters, to a five, defined as complete power ("real authority") of the plant manager, and intermediate scores varying degrees of joint decision making. In Table A2 we detail the individual questions (D1 to D4) and scoring grids in the same order as they appeared in the survey.

Since the scaling may vary across all these questions, we converted the scores from the four decentralization questions to z-scores by normalizing each score to have a mean of zero and standard deviation one. In our main econometric specifications, we take the unweighted average across all four z-scores as our primary measure of overall decentralization[18]. We also experiment with other weighting schemes and we also show what happens when the questions

[18] The resulting decentralization variable is itself normalized to mean zero and standard deviation one.

are disaggregated into their component parts.

4.1.3 Measuring Worker Autonomy

During the survey we also asked two questions about worker autonomy over production decisions regarding the pace of work and the allocation of production tasks. These questions were taken directly from Bresnahan et al. (2002) and are reported in Table A2 (questions D6 and D7). These questions are scaled on a one to five basis, with a one denoting managers have full control, and a five denoting workers have full control over the pace of work and allocation of tasks. Our measure of workers' autonomy is a dummy taking value one whenever decisions on both pace of work and allocation of production tasks are mostly taken by workers (i.e. both variables take values higher than three[19]). Again, we experiment with other functional forms.

4.1.4 Measuring Span of Control

We also asked about the plant manager's span of control in terms of the number of people he directly manages, as reported in Table A1 (question D8). The interviewers were explicitly trained to probe the number of people that *directly* report to him rather than the total number in the hierarchy below him. Unfortunately, we do not have such a direct measure of CHQ span (since we did not interview the CEO). But we try to get a sense of senior management's (CHQ) span of control by asking about whether the firm was single or multi-plant firm, with the idea being that multi-plant firms lead to larger spans at senior management level.

4.2 Harte-Hanks' ICT Data

We use an plant level ICT panel produced by the information company Harte-Hanks (HH). HH is a multinational firm that collects detailed hardware and software information to sell to large ICT firms, like IBM and Cisco, to use for marketing. This exerts a strong market discipline on the data quality, as major discrepancies in the data are likely to be rapidly picked up by HH customers'. For this reason, HH conducts extensive internal random quality checks on its own data, enabling them to ensure high levels of accuracy.

The HH data has been collected annually for over 160,000 plants across Europe since the late-1990s. They target plants in firms with 100 or more employees, obtaining a 37% response rate. We use the data for the plants we were able to match to the firms in the management survey. Since this matching procedure sometimes leads to multiple plants sampled in HH per firm, we aggregate ICT plant level data to the firm level, using employment weights. A number

[19] Decisions on pace of work are taken mostly by workers 11% of the times. Similarly, decisions on the allocation of production tasks, are taken moslty by workers 12% of the times.

of papers, such as Bresnahan et al (2002) and Brynjolfsson and Hitt (2003), have previously used the US HH hardware data, but few papers have used the software data. And certainly no one has combined the software data with information on organizational form in a single country, let alone internationally as we do here.

The prior literature, which has focused on hardware, has typically used information on firms aggregate ICT capital stock covering PCs, servers and infrastructure. But since these simultaneously reduce information and communication costs we do not expect a clear result. Our approach consists instead in considering the presence of specific technologies within the organization, namely: networks, to proxy for communication costs; Enterprise Resource Planning (ERP), to capture the reduction in information access costs for non-production decisions; and CAD/CAM to capture the reduction in information access costs for production decisions. This is depicted in relation to the model in Figure 4.

[Figure 4 about here]

HH contains information on the presence of all of these software types in the plant.

- HH distinguishes up to 17 distinct types of $ERPs$: the market leader is SAP, but Oracle, IBM and many others all offer products in this space. HH tries to record only ERP systems in operation (rather then those pending the go-live decision) which Aral, Brynjolfsson and Wu (2009) highlight as important.

- HH defines under "workstation applications" the presence of CAD/CAM's, software tools that assist production workers, engineers and machinists.

- HH measures the presence of Leased Lines or Frame Relays ($NETWORK$), which are technologies used by businesses to connect offices or production sites[20]. We have, in some years, direct information on Local Area Networks (LAN) and Wide Area Networks (WAN) and find these to be both highly correlated with our $NETWORK$ variable. In the robustness tests we show the similarity of results when using this as an alternative proxy for networks.

[20] A leased line is a symmetric telecommunications line connecting two locations. It is sometimes known as a 'Private Circuit' or 'Data Line'. Unlike traditional PSTN lines, a leased line does not have a telephone number, because each side of the line is permanently connected to the other. Leased lines can be used for telephone, data or Internet services. Frame relay is a data transmission technique used to send digital information (data and voice) cheaply quickly, and is often used in local and wide area networks. These systems are predominantly used to manage internal communication systems. They are not specifically about production or non-production decisions, but affects communication through out the firm.

The presence of any of these technologies at the plant level is codified using binary variables, and plant level employment weights are used to generate firm level indicators[21]. In terms of other technologies we condition on computers per worker, but note its theoretical ambiguity.

4.2.1 Does ERP mainly lower information costs rather than communication costs?

We have argued in Section 2 that ERP reduces information costs much more than communication costs, but this may be contentious. To investigate this issue in more detail, we collected data in a survey of IT managers on ERP usage in 431 firms with 100 to 5000 employees (details in Appendix B). Briefly, we asked managers specifically what was the impact of ERP in their companies with regards to information and communication. Following the theory, we asked them whether ERP was "used to endow top management with more and better information" and respondents could answer on a Likert scale of 1 = "strongly disagree" to 5 = "strongly agree". About three quarters of respondents said that ERP was "likely" or "very likely" to increase information flows (see Q1 in Figure 5). We also asked whether "ERP is used for faster communication of information and directives from top management to other employees" (again from 1 = strongly disagree to 5 = strongly agree). Only about a third of respondents answered that ERP was "likely" or "very likely" to increase this form of communication (see Panel Q2 in Figure 5). Using the cardinal scale, the mean of the information acquisition answer was 3.8, whereas the mean of the communication answer was 2.8 with the difference significant at the 1% level. A similar pattern is evident when respondents where asked about information acquisition vs. communication for middle managers (see Panels Q3 and Q4 in Figure 5). Appendix B has some further analysis, but this empirical evidence corroborates our discussions with technology experts that ERP is primarily related to information acquisition rather than communication.

[Figure 5 about here]

4.3 Other Data

In addition to the organization variable, the CEP survey also provides a wide variety of other variables such as human capital, demographics and management practices. Also, since the CEP survey used accounting databases as our sampling frames from BVD (Amadeus in Europe and ICARUS in the US), we have the usual accounting information for most firms, such as employment, sales, industry, location, etc.

[21] The resulting variables have mass points at zero or one.We present robustness tests using just the discrete versions of these technology indicators.

Table 2 contains some descriptive statistics of the data we use. In the largest sample we have 949 plants with median employment of 252 employees (153 at the median).

5 Empirical Results

5.1 Econometric Model

We wish to estimate the following generic equation:

$$O_{ijk} = \alpha a_{ijk} + \beta h_{ijk} + x'_{ijk}\gamma + u_{ijk} \tag{4}$$

where the dependent variable is O_{ijk} which denotes the organizational form of firm i in industry j in country k. Our theory offers predictions over four types of organizational outcomes for which we have data: the autonomy of the worker (O = AW), the autonomy of the plant manager (O = AP), the span of control of the plant manager (O = SP) and the span of control of the CHQ (O = SC). As in the theory, a denotes information access costs and h denotes communication (helping) costs. The x_{ijk} denote other control variables and u_{ijk} is a stochastic error term - we will discuss these in more detail later.

As discussed in the data section, we have direct measures of workers' autonomy, managers' autonomy and managers' span of control from our survey. The management autonomy questions investigate the extent of "non-production" autonomy the plant manager has from the central head quarters (e.g. how much investment could be made without central head quarters approval). The worker autonomy questions relate to decisions the worker could have control over compared to the plant manager (e.g. setting the pace of work).

The information costs and communication costs facing the firm are not directly observable, but we substitute in the relevant indicator from HH ($NETWORK$ lowers h; ERP and CAD/CAM lower a). To be more explicit the three regressions we will estimate are:

Autonomy of the plant managers

$$AP_{ijk} = \alpha^{AP} ERP_{ijk} + \beta^{AP} NETWORK_{ijk} + x'_{ijk}\gamma^{AP} + u^{AP}_{ijk} \tag{5}$$

Autonomy of the worker

$$AW_{ijk} = \alpha^{AW} (CAD/CAM)_{ijk} + \beta^{AW}_{ijk} NETWORK_{ijk} + x'_{ijk}\gamma^{AW} + u^{AW}_{ijk} \tag{6}$$

Span of control of the plant manager

$$\ln(SP_{ijk}) = \alpha^{SP} (CAD/CAM)_{ijk} + \beta^{SP}_{ijk} NETWORK_{ijk} + x'_{ijk}\gamma^{SP} + u^{SP}_{ijk} \tag{7}$$

Recall that Table 1 contains the main theoretical predictions of the model that we have sketched together with the technologies we are using. Falls in information costs are associated with greater plant manager autonomy and workers' autonomy, and larger spans of control. By contrast, falls in communication costs are associated with decreases in autonomy and ambiguous effects on spans.

We have a rich set of controls to draw on (x_{ijk}), although we are careful about conditioning on factors that are also directly influenced by technology. Consequently we consider specifications with very basic controls as well as those with a more extensive vector of covariates. Since there is measurement error in the organizational variables we generally condition on "noise controls" that include interviewer fixed effects and interviewee controls (e.g. tenure of manager) and interview controls (e.g. time of day). Other controls include a full set of three digit industry and country dummies, plant age, skills (share of college educated workers), firm and plant size and multinational status. We also perform robustness checks with many other variables suggested in the literature which may potentially confound our key results.

5.2 Basic Results

Tables 3 through 5 present the main results, each table has a different dependent variable and corresponds to equations (5) to (7). Table 3 contains the empirical results for plant managers' autonomy. All columns control for size (through employment of the firm and the plant), multinational status (foreign multinational or domestic multinational with the base as a purely domestic firm), whether the CEO is located on the same site as the plant manager[22], "noise" controls as discussed in the data section and a full set of country and three digit industry dummies. Column (1) uses the presence of Enterprise Resource Planning (ERP) as a measure of information acquisition over non-production decisions. As the theory predicts, ERP is associated with more autonomy of plant managers (relative to the central head quarters) as the plant manager is allowed greater flexibility in making decisions over investment, hiring, marketing and product introduction[23]. In our model this is because ERP enables him to access information more easily and solve more problems without referring them upwards. In terms of the other covariates we find that larger and more complex enterprises (as indicated by size and multinational status) are more likely to decentralize decision-making to the plant

[22] All results are robust to dropping size, multinational and ceo on site controls (results available upon requests). Note that firms where the CEO was the same individual as the plant manager are dropped.

[23] We investigate the endogeneity of the technology variables in depth in Table 6. One inital check on whether the OLS results are upwards biased is to implement a propensity score matching technique. We found that matching strengthened the results. For example in the specification of column (2) of Table 6, the Average Treatment effect on the Treated was 0.299 with a standard error of 0.101. This used nearest neighbors matching with three neighbors.

manager. Column (2) includes firm level skills, as measured by the proportion of employees with college degrees. The variable takes a positive and significant coefficient, indicating that more skilled workplaces tend to be more decentralized (consistent with Caroli and Van Reenen, 2001). This column also includes the computers intensity of plant which enters with a negative and insignificant sign. The ambiguity of the IT hardware variable should not be surprising as greater computer intensity simultaneously lowers information costs and communication costs which, according to our theoretical model, have opposite effects on autonomy.

The third column of Table 3 includes an indicator for the presence of networks, which indicates lower communication costs. As the theory predicts, there is a negative coefficient on the network variable (significant at the 5% level) which may reflect the fact that lower communication costs imply that central head quarters make more decisions than the plant manager as it is now easier to pass on solutions. This result is robust to including skills and computer intensity in column (4). Columns (5) and (6) includes both information and communications technologies at the same time. Since these are positively correlated, the results are a little stronger[24]. Table 3 is consistent with the theoretical model sketched earlier: falling information costs are associated with decentralization, whereas falling communication costs are associated with centralization.

The next two tables analyze the relationship between information and communication technologies with workers' autonomy and plant manager span of control (this follows exactly the order outlined in Table 2). Table 4 is a probit model of workers' autonomy where our indicator of information acquisition over production decisions is CAD/CAM. In columns (1) and (2), the coefficient on CAD/CAM is positive and significant, indicating that such technologies are associated with worker empowerment. In columns (3) and (4), by contrast, the presence of networks has a negative coefficient which is consistent with the theoretical notion that greater communication leads to centralization. Although the coefficient on $NETWORK$ is correctly signed, it is insignificant even when both technologies are included simultaneously (in the final two columns).

Table 5 examines the plant manager's span of control as measured by the number of employees who directly report to him. CAD/CAM is associated with significantly *greater* plant manager span, consistent with the idea that production technologies that help worker information access enable them to do more tasks which makes it possible for the plant manager to oversee more production workers (greater span). The coefficient on $NETWORK$ is positive

[24] The results are robust to clustering at a higher level, such as by industry country cell. For example, in the final column the coefficients(standard errors) are 0.116(0.050) and 0.110(0.053).

and insignificant (the theory does not have an unambiguous prediction for this coefficient).

Comparing the empirical results with our expectations in Table 1, we obtain a reasonably close match. All the coefficients are in the same direction as the theoretical predictions (when they are unambiguous) and all are significant at the 5% level (with the exception of $NETWORK$ in the worker autonomy equation). The idea that information technologies are associated with increased autonomy and span of control, whereas communications technologies are associated with decreased autonomy appears to have some empirical content. By contrast, the automation story would predict information technologies should be associated with centralization away from lower level employees and the coordination theories would predict that communication technologies should be associated with decentralization (see sub-section 3.3.). Thus, we interpret our evidence on ICT and firm organization as providing some support for the cognitive view of hierarchies in section 2.

5.3 Magnitudes

Although the estimates are statistically significant and broadly consistent with our theory, are they of economic significance? One way of examining this question is to simulate an increase in the diffusion of our ICT indicators. Given the debate over whether the increasing productivity gap between Europe and the US in the decade since 1995 was related to ICT (e.g. Bloom, Sadun and Van Reenen, 2007), we simulate increasing the ICT diffusion measures by 60% (the difference in the average level of the ICT capital stock per hour worked between the EU and the US during 2000-2004)[25].

An increase in the penetration rate of ERP of 60% over the sample average of 36% is 22 percentage points. Using the final column of Table 3, this is associated with a 0.025 of a standard deviation increase in plant manager autonomy. This is equivalent in effect to an increase in the proportion of college graduates by 26% (using the coefficient on education), which is broadly the increase in education achieved by the US between 1990 and 2000 of about a quarter[26]. So we regard this as a substantial effect. Similar calculations show that increasing the penetration of $NETWORK$ by 60% (21 percentage points at the mean) is associated with a decrease in plant manger's autonomy by 0.023 standard deviations, equivalent to reducing the college share by 24%. This increase in $NETWORK$ is associated with an increase in plant manager's span of 1.1% (equivalent to a 19% increase in the college share) and with

[25] This is based on the EU KLEMS data. See Timmer, Yppa and Van Ark (2003) Table 5 for a similar figure for 2001 and a description of the data.

[26] In 1990 25.7% of American workers had college degrees or equivalent and this rose to 31.8% by 2004, an increase of 6.1 percentage points or 23.7% (Machin and Van Reenen, 2008).

a reduction in worker autonomy of -0.005 standard deviations (equivalent to a 10.3% fall in the college share)[27]. So the "effect" of falling communication costs ($NETWORK$) appears somewhat greater for plant manager autonomy than for worker autonomy, with span of control in the middle. Finally, consider a 60% increase in CAD/CAM. This is associated with 0.2% increase in plant manager's span (equivalent to a 3.7% increase in the college share) and a 0.1% increase in worker autonomy (equivalent to a 1.6% increase in the college share). This is lower because the mean of CAD/CAM is lower than the other technologies.

This implies that these technical changes appear very important for some aspects of organization (benchmarked against equivalent increases in skills), especially ERP on plant manager's autonomy and $NETWORK$ on all three organizational dimensions.

5.4 Endogeneity and Robustness

5.4.1 Endogeneity

Tables 3 through 5 present conditional correlations that seemed to be broadly consistent with the theory. The theoretical model suggests that the endogenous outcomes should covary in systematic ways in equilibrium which is what we examine in the data. We are of course concerned about endogeneity bias as there may be some unobservable that is correlated with the organizational outcomes and our measures of information and communication costs (especially as these are all measured at the firm level). We take some reassurance in the fact that although these ICT indicators are positively correlated in the data[28], their predicted effects on the same organizational variable can take opposite signs. For example, in the plant manager autonomy equation the coefficient on information acquisition technologies (proxied by ERP) is opposite in sign to communication technologies ($NETWORK$) both theoretically and empirically. For endogeneity to generate these results, the hypothetical unobservable positively correlated with decentralization would have to mimic this pattern of having a negative covariance with $NETWORK$ and a positive covariance with ERP. This is always a theoretical possibility, but it is not obvious what would generate this bias.

In this sub-section we consider instrumental variable strategies for ERP and $NETWORK$[29]. SAP is the market leader in ERP and was founded by five IBM engineers who formed their start-up in Walldorf, a suburb of the German city of Heidelberg in 1972 (Hagiu et al, 2007). SAP's Headquarters remains in Walldorf. Studies of diffusion suggest that geography plays an

[27] These calculations use the coefficients in the final columns in Tables 4 and 5.

[28] For example, the pairwise correlation between the ERP and the $NETWORK$ variables is 0.168, significant at the 1% level.

[29] We do not have an obvious instrumental variable for CAD/CAM, so we can only re-estimate Table 3 using this alternative identification strategy.

important role because when there is uncertainty and tacit knowledge, being geographically close to the innovator plays a role in the adoption of the new technology. Studies of the diffusion of ERP (e.g. Armbruster et al, 2005) suggest that firms closer to SAP's headquarters were more likely to be early adopters. Since our firms are medium sized enterprises who could also learn from these earlier adopters (ERP is more common among very large enterprises), we use the closeness to Walldorf as an exogenous factor that shifts the probability of adopting an ERP. We focus on Continental Europe as the US and UK are separated by sea from Germany, and drop subsidiaries of multinational firms as it is harder to pinpoint the appropriate distance measure for such global firms.

We regress the presence of ERP in the plant on the ln(distance in kilometers) to Walldorf in Column (1) of Table 6. Consistent with our priors, a firm twice as far as another from Walldorf is over 20% less likely to adopt an ERP system. When entered instead of ERP in the plant manager autonomy equation (the "reduced form" of column (2)), the coefficient on distance is again negative and significant. Column (3) presents the instrumental variable results, showing that ERP has a large and positive causal effect on decentralization[30].

In the sample of Table 6 there are 45% of firms with ERP, of whom 30% use SAP and 70% use a variety of other ERP offered by vendors like Oracle, Sage and Microsoft. Since our instrumental variable should be most powerful for SAP we repeated the specifications of columns (1)-(3) replacing ERP with a dummy for the presence of SAP's ERP only. The results are much stronger: the first stage coefficient (standard error) was -0.211(0.062) and the second stage coefficient (standard error) was 1.948(0.675). In fact, the instrument has no power at all for predicting non-SAP ERP systems. Given the distance to Walldorf only predicts the adoption of SAP ERP and not other makes of ERP this suggests it reflects some SAP effect rather than some other unobservable favorable to ERP adoption.

We consider an alternative approach to identifying the effects of networks. The cost of electronically communicating over networks differs substantially between countries because of differential degrees of the roll-out of high speed bandwidth and the pricing of telecommunications. Although there have been moves to liberalize the telecommunication sector in most countries, this has happened at very different speeds and in some countries the incumbent state run (or formerly state run) monopolists retain considerable pricing power (e.g. Nicoletti and Scarpetta, 2003; Azmat et al, 2008; OECD, 2005, 2007). We discuss these more in Appendix C.

[30] We experimented with including all the multinational subsidiaries in the regression (473 firms). As expected the first stage was weaker with a coefficient (standard error) on distance of -0.098(0.053). Nevertheless, the second stage remained weakly significant with a coefficient (standard error) on ln(distance) of 1.745(0.885).

We exploit these differential costs using OECD (2007) series on the prices of leased lines used for networks (call this price p_k^c), which represent the cost of an annual subscription to a leased line contract at 2006 PPP US$. An obvious empirical problem is that these measured telecommunication price indices only vary across countries[31] and not within countries, so they are collinear with the country dummies. Industries will be differentially affected by these costs, however, depending on the degree to which they are reliant on networks for exogenous technological reasons. We proxy this reliance by using the intensity of network use in the industry pooling the data across all countries ($NETWORK_j$).[32] The instrument is defined as $p_k^c * NETWORK_j$ where we include a full set of industry and country dummies, so we are essentially using $p_k^c * NETWORK_j$ as a direct proxy for communication costs, h, with the prediction that for the network-intensive industries we would expect to see more managerial autonomy in countries where communication prices are high (like Poland) than where they are low (like Sweden).

The results for this experiment are presented in columns (4)-(6) of Table 6. High telecommunications costs significantly reduce the probability of having a network. When this is entered in the reduced form in column (5), the variable enters with the expected positive sign: less networks imply more decentralization[33]. In column (6), the second stage coefficient is large, negative and significant as predicted by the theory[34].

The final four columns of Table 6 use both instruments together. The first stages are presented in columns (7) and (8). The reduced form in column (9) shows the expected signs for both instruments: distance from SAP's birthplace reduces decentralization, whereas communication costs increase decentralization. Using these variables as instruments in the final column shows the theoretically expected results we saw from the OLS tables: ERP causes more decentralization and $NETWORK$ less decentralization[35]. Note that the magnitude of the effects is much larger than in the simple OLS specifications. This could be due to correct-

[31] This is only partially true as there is some within country variation. For example, the roll-out of broadband proceeds at a different rate across areas (see Stephenson, 2006).

[32] This identification strategy parallels Rajan and Zingales (1998) We also considered specifications where we used network intensive industries defined on US data only and dropped the US from the sample we estimated on. This generated similar results.

[33] We also ran these regressions on the larger sample that includes the US and UK and multinationals (982 firms) with similar results. For example, in an equivalent specification of the reduced for column (5) the coefficient (standard error) on the instrument was 4.643(2.112) in this larger sample.

[34] A concern is that the country-level network price variable simply proxies some other variable so we also included country-level schooling and GDP per person interactions with industry network use. These were both insiginificant with coefficients (standard errors) of -3.805(12.060) and -9.307(7.927) respectively.

[35] The results are robust to including various other regional controls. For example, we included regional ln(GDP per head) and population density in the final column of Table 6. The coefficient (standard error) on ERP and $NETWORK$ were 2.029 (0.869) and -3.011(1.483) respectively.

ing attenuation bias and reverse causality - for example, plants which are for some exogenous reason more decentralized may find it difficult to coordinate on introducing an ERP system which will require some consolidation of databases. Furthermore, the OLS estimates are also slightly larger on this sub-sample of domestic firms[36]. Whatever the exact reasons for the lower OLS estimates compared to the IV coefficients, taking Table 6 as a whole suggests that the effects we identify are causal impacts of technology on organizational form, rather than simply reflecting an endogeneity problem.

5.4.2 Robustness

We have examined a large variety of robustness tests and some of these are presented in Table 7. Each panel presents a different dependent variable with different tests in each column (Panel A for plant manager autonomy, Panel B for worker autonomy and Panel C for plant manager span of control). Column (1) simply repeats the baseline specifications from the final column in Tables 3 through 5.

In Bloom, Sadun and Van Reenen (2009) we found that product market competition and cultural factors such as trust and non-hierarchical religions were associated with greater plant manager autonomy. We control for these in column (2) by including a full set of regional dummies and the industry-level Lerner Index of competition. None of the main results change, with the exception of $NETWORK$ in the worker autonomy equation. The sign is still negative, which is consistent with the theory (falls in communication cost lower autonomy) but it is now larger in absolute magnitude and significant at the 10% level, whereas it was insignificant in the baseline regression. Column (3) includes a variety of additional firm level controls: the capital-labor ratio, sales per employee, total employment in the group where the firm belongs (i.e. consolidated worldwide employment for multinationals), firm age and a listing dummy. The results are robust to these additional controls (which were individually and jointly insignificant). Column (4) uses an alternative indicator of networks based on the presence of LAN (Local Area Networks) or WAN (Wide Area Networks)[37]. The LAN/WAN indicator is highly correlated with $NETWORK$ and the results are very similar to the baseline. The only difference is that, again, $NETWORK$ in the worker autonomy equation which is now significant (at the 5% level) with a theory consistent negative sign. Note that our ICT variables from HH are averaged over all the plants in the firm using plant employment as weights.

[36] The OLS equivalent of column (10) has a coefficient of 0.151 on ERP and -0.220 on $NETWORK$. The equivalent coefficients from column (6) of Table 3 are 0.116 and -0.110 respectively.

[37] We prefer our indicator of $NETWORK$ as LAN was included only in earlier years of the Harte-Hanks data and WAN only in later years.

Although these are usually either one or zero, in-between values are also possible. We consider a discrete alternative where all the firms with non-zero values of ICT are coded as unity and present these results in column (5). Again, nothing much changes, nor does including the Bloom and Van Reenen (2007) measure of management quality in column (6). Column (7) considers alternative ways of constructing the dependent variable. For the plant manager autonomy equation we use the principal component of the four questions and for the worker autonomy question we define it based only on the pace of work[38]. The results again seem robust to these alternatives. Column (8) drops the size controls as they are potentially endogenous and column (9) conditions on the sub-sample with at least three firms per industry. Neither experiment has much effect on the results.

5.5 Extensions

Finally, we investigate a further set of extensions and tests of the theory.

5.5.1 "Cross" Effects of Technologies

We start by considering some of the "cross" effects of technologies by saturating the empirical models with all three types of technologies. Table A3 in the Appendix presents the full set of predictions from the theory analogously to Table 1. We present the most general specifications for each of the three main organizational variables in Appendix Table A4. The first thing to note is that none of the earlier conclusions change with respect to the earlier tests: $NETWORK$ are associated with less autonomy, ERP is associated with more autonomy for managers and CAD/CAM is associated with more autonomy for workers and a larger span of control. In terms of the additional tests, the first row of Table A4 includes CAD/CAM in the plant managers' autonomy equation. This is insignificant, in line with the theoretical prediction of a zero effect. The last row includes ERP in the workers' autonomy equation, which is negative (as theory predicts), but insignificant. The last row also includes ERP in the span of control regression, which takes a positive coefficient. This is the only place we obtain a sign which is contrary to the theory as it should be negative. We do not regard this as undermining our general set-up, however, as the coefficient is insignificant. The robustness of the earlier results to these "cross effects" is reassuring, but the insignificance of the extra terms does imply that it is difficult to pick up some of the more subtle cross effects of ICTs on firm organization.

[38] The results are also robust to constructing the plant manager autonomy variable focusing solely on questions coded between 1 and 5, i.e. excluding the question on how much capital investment a plant manager could undertake without prior authorization from CHQ.

5.5.2 Corporate Head Quarters' Span of Control

Table A3 showed that the theory also generates predictions for the span of control of the CHQ. Although we had a direct measure of the plant managers' span (number of direct reports) we do not have such a direct measure for the CHQ span. One proxy measure for this, however, is the number of plants in the firm, with more plants indicating a larger CHQ span. Because this variable is likely measured with error we simply consider a dummy for a multiplant firm as a measure of the CHQ span and regress this on information acquisition technology for the Plant Manager (ERP) and $NETWORK$ in Appendix Table A5. The clear theoretical prediction is that ERP should be associated with a wider CHQ span because plant managers are able to make decisions more easily so CHQ finds it easier to manage a larger number of them. This is supported by Table A5: ERP has a significant and positive association with CHQ span of control in column (1) where we condition on the standard controls and column (3) where we also condition on $NETWORK$[39]. The coefficient on $NETWORK$ is positive and significant (it has a theoretically ambiguous sign).

5.5.3 An alternative mechanism: Incentives

At the end of the theory section we discussed alternative mechanisms, such as agency and incentives, through which ICT could affect organizational structure. We argued that the cognitive approach we take here is first order, although they may still be important. One simple way to investigate this is to explicitly condition on incentive pay in the regressions. From the survey we know the proportion of managerial pay that was in bonus (direct incentive pay) and the increase in pay upon promotion (a career concerns mechanism).

Columns (1) through (3) of Table A6 include a variable indicating the proportion of the plant manager's pay that was bonus (rather than flat salary)[40]. Columns (4) through (6) includes the proportionate increase in pay when promoted for a typical plant manager. It is clear that the signs and significance of the technology variables are hardly affected by this additional variable. For example, in column (1) the incentive pay variable is positively and significantly associated with greater autonomy of the plant manager. This seems sensible - there is little point in having performance related pay if the manager has no discretion over relevant decisions. Nevertheless, the coefficient on ERP has fallen only to 0.115 (from 0.116 in Table 3) and the coefficient on $NETWORK$ to -0.110 (unchanged from Table 3). The other incentive pay proxies are insignificant and do not change the qualitative results. Obviously this

[39] If we also include CAD/CAM the ERP coefficient remains positive and significant. The theory predicts a zero effect of CAD/CAM which indeed has an insignificant coefficient (-0.389 with a standard error of 0.432).

[40] See Lemieux, MacLeod and Parent (2007) for how performance pay has grown in importance over time.

is a crude test as there are other dimensions of incentive pay we have not captured (e.g. for production workers) and some incentive effects may operate independently of any remuneration scheme. But the robustness of our results to explicit controls for incentives suggest that there is an important role for the cognitive theory we emphasis when looking at the impact of ICT.

6 Conclusions

The empirical and theoretical literature that examines the economic effects of information and communication technologies (ICT) generally aggregates together the information technology (IT) and communication technology (CT) into a single homogeneous mass. We argue that this is inappropriate because the impact of IT and CT on the organization of firms, and ultimately income inequality, will be quite different depending on the type of technology. Falls in communication costs will tend to reduce employee autonomy, as decisions will be passed up to the centre of the firm. Falls in information acquisition costs will have the opposite effect, facilitating more effective employee decision-making.

We show these effects formally in a "cognitive" model of firm organization which considers two types of decisions within firms. First, we consider non-production decisions (investment, hiring, new products and pricing). These decisions can either be taken by the CEO at central head quarters or by the plant manager in the local business unit. The key piece of information technology that has affected these decisions is Enterprise Resource Planning. ERP provides a range of data on metrics like production, waste, energy use, sales, inventories and human resources. Modern ERP systems increase dramatically the availability of information to managers, which should (according to our theory) be associated with decentralization of decision making.

Second, we consider factory floor decisions, on the allocation and pace of production tasks. These production decisions can either be taken by factory floor employees or by their superiors in the plant hierarchy, like the plant managers. Here, a key technological change has taken the adoption of Computer Assisted Design and Computer Assisted Manufacturing (CAD/CAM). A worker with access to those technologies can solve design and production problems better, and thus needs less access to his superiors in making decisions. This should lead to the decentralization of non-production decisions.

Of course both production and non-production decisions will also be impacted by reducing communication costs. The key technological innovation in within-firm communications is the growth of networks. The spread of networks should therefore be associated with centralization of both types of decisions within the firm, as decision making is more easily passed up the firm

to higher level managers.

We confirm these predictions on a new dataset that combines plant-level measures of organization and ICT hardware and software adoption across the US and Europe. The organizational questions were collected as part our large international management survey, and were explicitly targeted at the theories we investigate.

In terms of identification, we mainly focus on simple conditional correlations between the different ICT measures and the multiple dimensions of the organization of the firm, guided by our theoretical predictions. But we also show that treating technology as endogenous strengthen the results. Our instrumental variables are distance from the birthplace of the market leading *ERP* system (SAP) and the differential regulation of the telecommunication industry across countries (which generates exogenous differences in the effective prices of networks).

There are several directions we are currently pursuing in this line of research. Firstly, we are examining in more detail the reasons for differential adoptions of technologies across firms and countries as the instruments suggest important factors that could explain the diffusion of communication and information technologies. This is of interest in itself, but is also important in order to get more closely at the causal effects of changes in ICT on firm organization. Secondly, we are developing the theory to consider interactions between different type of production and non-production technologies at other layers of the hierarchy. Finally, we are examining the effect of differential type of IT adoption on other outcomes such as productivity and wage inequality at the level of the industry and economy.

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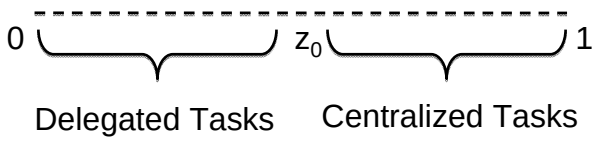
Figure 1: Delegation of tasks in the Basic Model



Notes: $z \in [0, z_0]$ Performed by lower level agents
$z \in (z_0, 1]$ Passed on to the higher level

Figure 2: Management span and autonomy

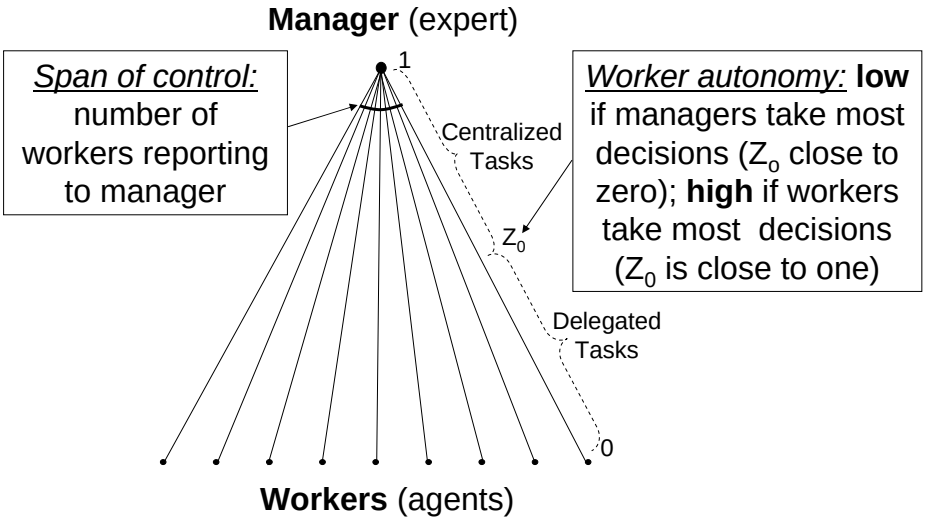
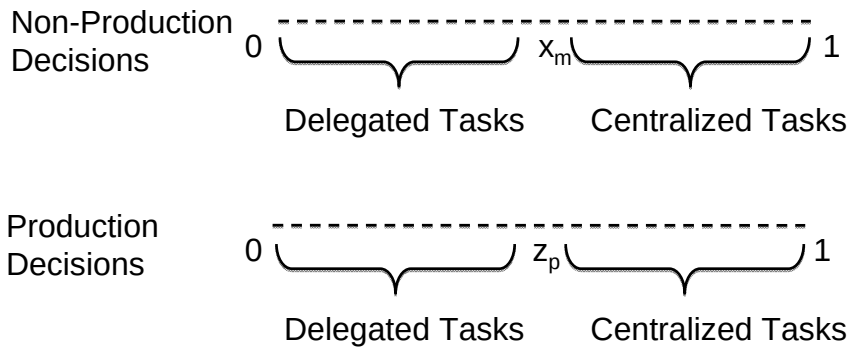


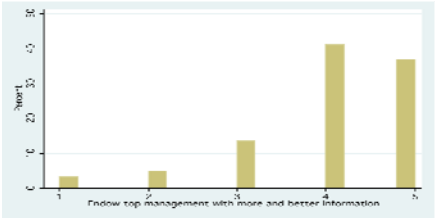
Figure 3: Delegation of tasks in the extended model



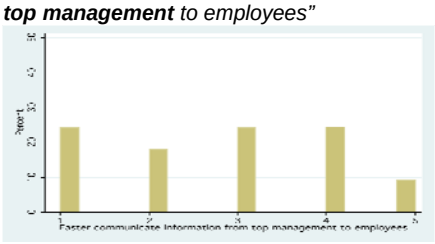
Notes: This generalizes Figure 1 where we allow for non-production decisions and production decisions. Non-production decisions below x_m are performed by plant managers, the rest by central head quarters. Production decisions below z_0 are performed by production workers, the rest by plant managers

Figure 4: Enterprise Resource Planning (ERP) use

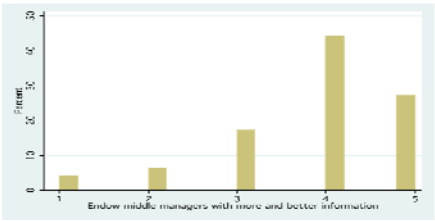
Q1: *"Our ERP System is used to endow **top management** with more & better **information**"*



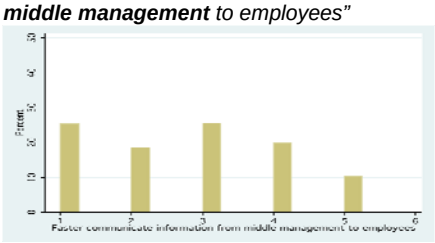
Q2: *"Our ERP System is used to faster **communicate** information and directives from **top management** to employees"*



Q3: *"Our ERP System is used to endow **middle management** with more & better **information**"*



Q4: *"Our ERP System is used to faster **communicate** information and directives from **middle management** to employees"*



Notes: Answers range from 1="strongly disagree" to 5="strongly agree". Each bar represents the % of respondents in the relevant bin from 431 firms. See Appendix B for details.

Figure 5: Information and communication

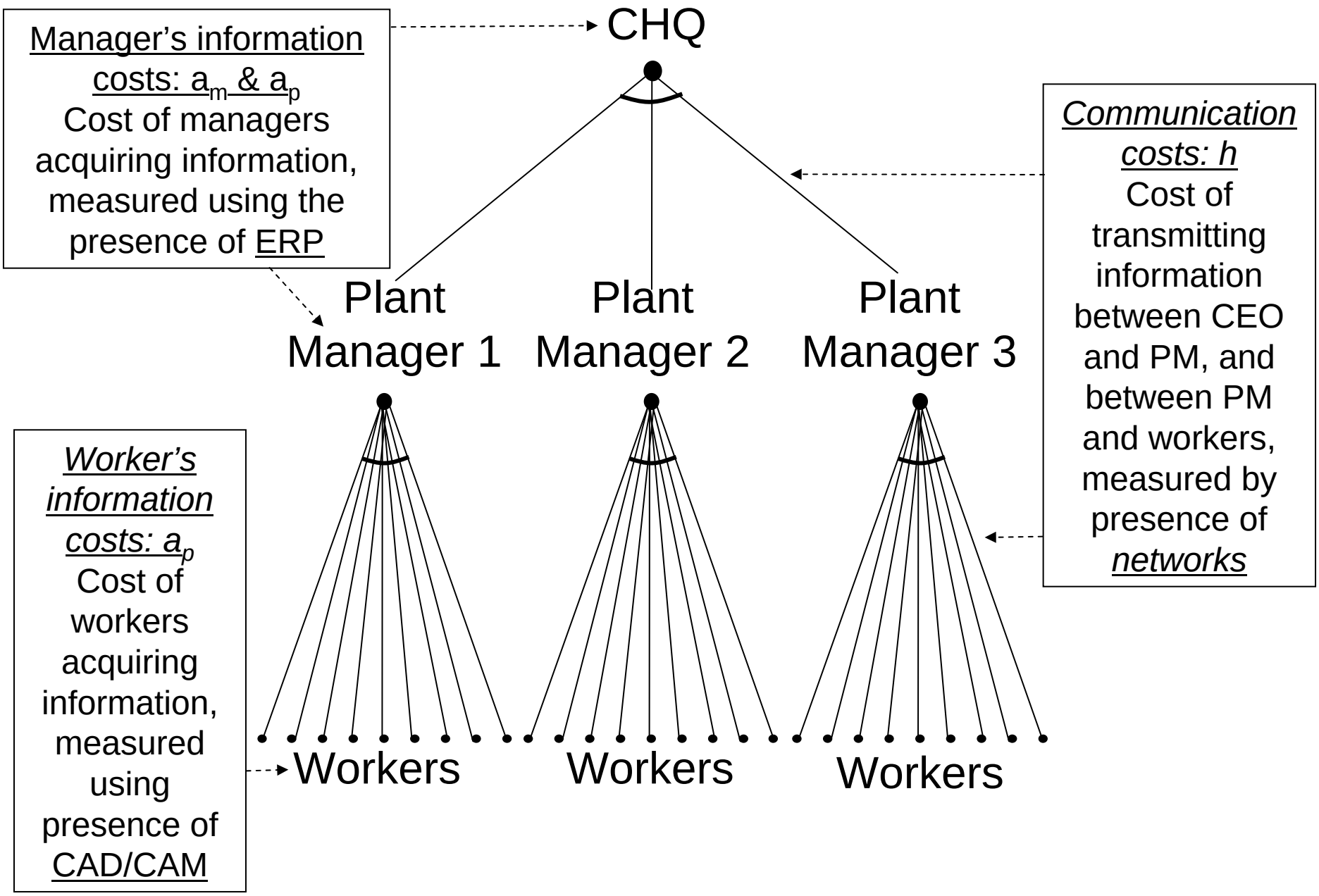


TABLE 1 – SUMMARY OF MAIN THEORETICAL PREDICTIONS THAT WE EMPIRICALLY TEST

		(1) Plant Manager Autonomy (Table 3)	(2) Worker Autonomy (Table 4)	(3) Plant Manager Span of Control (Table 5)
Reduction in Communication costs *(h)*	*Technology Indicator*	*NETWORK (h)*	*NETWORK (h)*	*NETWORK (h)*
	Theoretical Prediction	-	-	?
	Empirical Finding	-	-	+
Reduction in Information acquisition costs *(a)*	*Technology Indicator*	*ERP* (a_m)	*CAD/CAM* (a_p)	*CAD/CAM* (a_p)
	Theoretical Prediction	+	+	+
	Empirical Finding	+	+	+

Notes: This table presents the theoretical predictions and the empirical findings. Column (1) refers to plant manager autonomy; Column (2) refers to workers' autonomy; and Column (3) refers to span of control (for plant manager and CEO). *NETWORK* denotes the presence of a network (leased line/frame relay); *ERP* denotes the presence of Enterprise Resource Planning and *CAD/CAM* denotes the presence of Computer Assisted Design/Computer Assisted Manufacturing. A "+" denotes an increase, a "-'' a decrease a "0" denotes no effect and "?'' denotes an ambiguous sign. All empirical findings except for reduction in communication costs in Column (2) and (3) are statistically significant at the 5% level.

TABLE 2 - SUMMARY STATISTICS

Variable	Mean	Median	Standard Deviation	Firms
Employment (Firm)	960.142	350	3259.742	943
Employment (Plant)	252.664	155	286.087	911
Plant Manager Autonomy	0.252	0	0.982	948
Workers' Autonomy	0.076	0	0.265	935
Ln(Plant Manager SPAN)	1.892	2	0.521	874
CEO Span (Multi-plant dummy)	0.641	1	0.480	948
Computers per Employee	0.483	0	0.395	937
ERP	0.363	0	0.473	948
CADCAM	0.024	0	0.152	687
NETWORK	0.355	0	0.472	948
LAN/WAN	0.427	0	0.492	948
Foreign Multinational	0.350	0	0.477	948
Domestic Multinational	0.287	0	0.453	948
%College	16.007	10	17.169	867
Bonus as a % of salary	0.112	0	0.151	862
% Increase salary on promotion	0.215	0	0.189	610
Leased Line Price (PPP 2006 USD)	4984.281	5260	1439.319	948

Notes: These are descriptive statistics from the sample in Table 3 (except for CAD/CAM which is Table 4).

TABLE 3 - PLANT MANAGER AUTONOMY

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable	**Plant Manager Autonomy**					
ERP	0.097*	0.104*			0.114**	0.116**
	(0.053)	(0.054)			(0.053)	(0.054)
NETWORK			-0.107**	-0.098*	-0.123**	-0.110**
			(0.053)	(0.052)	(0.053)	(0.053)
Ln(Percentage College)		0.100***		0.097***		0.098***
		(0.032)		(0.032)		(0.032)
ln(Computers/Employee)		-0.041		-0.020		-0.031
		(0.031)		(0.031)		(0.031)
ln(Firm Employment)	0.070*	0.063	0.073*	0.068*	0.073*	0.067*
	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)	(0.040)
Plant Employment	0.151***	0.148***	0.151***	0.151***	0.149***	0.147***
	(0.044)	(0.045)	(0.044)	(0.045)	(0.044)	(0.045)
Foreign Multinational	0.177**	0.178**	0.202**	0.196**	0.193**	0.190**
	(0.080)	(0.080)	(0.079)	(0.079)	(0.080)	(0.080)
Domestic Multinational	0.195**	0.184**	0.208**	0.193**	0.203**	0.190**
	(0.082)	(0.083)	(0.082)	(0.083)	(0.082)	(0.083)
Number of Observations	3,434	3,434	3.434	3,434	3,434	3,434
Number of Firms	948	948	948	948	948	948

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. The dependent variable is the z-score of plant manager autonomy (mean=0 and standard deviation=1) across four questions relating to plant manager's control over hiring, investment, product introduction and marketing (see text). All columns are estimated by OLS with standard errors in parentheses (robust and clustered by firm). The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). All columns include a full set of three digit industry dummies and "Noise controls" (analyst fixed effects, plant manager seniority and tenure in company, the day of the week the interview was conducted, interview duration and reliability). "ERP" denotes Enterprise Resource Planning and "NETWORK" denotes the firm has an internal network (leased lines or frame relays). All columns exclude firms where the plant manager is the CEO and include a dummy equal to unity if the CEO is on site.

TABLE 4 – WORKERS' AUTONOMY

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable			**Workers' Autonomy**			
CAD/CAM	0.582**	0.540**			0.586**	0.535*
	(0.271)	(0.275)			(0.268)	(0.274)
	[0.073]	[0.055]			[0.072]	[0.053]
NETWORK			-0.214	-0.229	-0.218	-0.226
			(0.171)	(0.178)	(0.172)	(0.180)
			[-0.027]	[-0.023]	[-0.027]	[-0.023]
Ln(Percentage College)		0.467***		0.471***		0.468***
		(0.111)		(0.110)		(0.110)
		[0.047]		[0.048]		[0.047]
ln(Computers /Employee)		-0.026		0.003		-0.013
		(0.099)		(0.099)		(0.100)
		[-0.003]		[0]		[-0.001]
ln(Firm Employment)	-0.036	-0.039	-0.028	-0.027	-0.032	-0.033
	(0.104)	(0.103)	(0.104)	(0.102)	(0.103)	(0.102)
	[-0.005]	[-0.004]	[-0.003]	[-0.003]	[-0.004]	[-0.003]
Plant Employment	-0.113	-0.129	-0.116	-0.124	-0.117	-0.128
	(0.128)	(0.132)	(0.128)	(0.131)	(0.128)	(0.132)
	[-0.014]	[-0.013]	[-0.014]	[-0.013]	[-0.014]	[-0.013]
Foreign Multinational	0.385*	0.336	0.432*	0.384	0.417*	0.368
	(0.232)	(0.247)	(0.233)	(0.249)	(0.234)	(0.250)
	[0.055]	[0.039]	[0.062]	[0.045]	[0.059]	[0.042]
Domestic Multinational	0.336	0.247	0.372*	0.293	0.368	0.283
	(0.226)	(0.231)	(0.226)	(0.233)	(0.226)	(0.233)
	[0.046]	[0.027]	[0.052]	[0.033]	[0.05]	[0.031]
Number of Observations	874	874	874	874	874	874
Number of Firms	534	534	534	534	534	534

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. The dependent variable in all columns is a dummy equal to unity if the plant manager reports that tasks allocation and pace of work are determined mostly by workers (instead of managers). All columns are estimated by probit ML with standard errors in parentheses (robust and clustered by firm). Marginal effects (evaluated at the mean) reported in square brackets. All columns exclude firms where the plant manager is the CEO and include a dummy equal to unity if the CEO is on site. The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). A full set of three digit industry dummies and "Noise controls" (analyst fixed effects, plant manager seniority and tenure in company, the day of the week the interview was conducted, interview duration and reliability). "CAD/CAM" denotes Computer Assisted Design/ Computer Assisted Manufacturing and "NETWORK" denotes the firm has an internal network (leased lines or frame relays).

TABLE 5 - PLANT MANAGER SPAN OF CONTROL

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable	**Plant Manager Span of Control**					
CAD/CAM	0.167**	0.153**			0.168**	0.155**
	(0.072)	(0.076)			(0.072)	(0.076)
NETWORK			0.054	0.051	0.054	0.053
			(0.043)	(0.043)	(0.043)	(0.043)
Ln(Percentage College)		0.059**		0.061***		0.059**
		(0.023)		(0.023)		(0.023)
ln(Computers /Employee)		0.010		0.008		0.006
		(0.024)		(0.024)		(0.024)
ln(Firm Employment)	0.041	0.041	0.042	0.041	0.038	0.038
	(0.027)	(0.026)	(0.027)	(0.026)	(0.027)	(0.026)
Plant Employment	0.024	0.032	0.028	0.035	0.025	0.031
	(0.031)	(0.032)	(0.032)	(0.032)	(0.032)	(0.032)
Foreign Multinational	0.059	0.037	0.054	0.032	0.052	0.031
	(0.058)	(0.056)	(0.058)	(0.056)	(0.058)	(0.056)
Domestic Multinational	0.129**	0.105*	0.124**	0.100*	0.125**	0.102*
	(0.060)	(0.057)	(0.060)	(0.057)	(0.059)	(0.057)
Number of Observations	1,415	1,415	1,415	1,415	1,415	1,415
Number of Firms	859	859	859	859	859	859

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. The dependent variable in all columns is the log of the number of employees reporting directly to the plant manager. All columns are estimated by OLS with standard errors in parentheses (robust and clustered by firm). All columns exclude firms where the plant manager is the CEO and include a dummy equal to unity if the CEO is on site. The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). All columns include a full set of three digit industry dummies and "Noise controls" (analyst fixed effects, plant manager seniority and tenure in company, the day of the week the interview was conducted, interview duration and reliability). "CAD/CAM" denotes Computer Assisted Design or Manufacturing software and "NETWORK" denotes the firm has an internal network (leased lines or frame relays).

TABLE 6 – PLANT MANAGER AUTONOMY, INSTRUMENTAL VARIABLE ESTIMATES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Dependent Variable	**ERP**	**Plant Manager Autonomy**	**Plant Manager Autonomy**	**NETWORK**	**Plant Manager Autonomy**	**Plant Manager Autonomy**	**ERP**	**NET-WORK**	**Plant Manager Autonomy**	**Plant Manager Autonomy**
Regression	**1st Stage**	**Reduced Form**	**2nd Stage**	**1st Stage**	**Reduced Form**	**2nd Stage**	**1st Stage**	**1st Stage**	**Reduced Form**	**2nd Stage**
ERP			1.892**							1.569**
			(0.934)							(0.692)
NETWORK						-1.720**				-2.120**
						(0.815)				(1.081)
Ln(Distance to Walldorf)	-0.217**	-0.410**					-0.217**	0.034	-0.411**	
	(0.081)	(0.180)					(0.081)	(0.066)	(0.179)	
Ln(NETWORK Price) *(Industry NETWORK Intensity)				-3.196**	5.495**		-0.798	-3.198**	5.528**	
				(1.214)	(2.351)		(1.775)	(1.226)	(2.510)	
Number of observations	493	493	493	493	493	493	493	493	493	493
Number of firms	161	161	161	161	161	161	161	161	161	161

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. The dependent variable is the z-score of plant manager autonomy. Standard errors are robust and clustered at the regional level in all columns (54 regions). All columns exclude firms where the plant manager is the CEO and include a dummy equal to unity if the CEO is on site. The sample includes firms based in France, Germany, Italy, Portugal, Poland and Sweden (country dummies included). All multinational subsidiaries are dropped. All columns include noise controls, firm controls and industry dummies as in previous tables. The instrument for ERP is the distance (in km) from Walldorf, Heidelberg (the head quarters and founding place of SAP). The instrument for Networks is the cost of communications interacted with industry-level network intensity. "Industry NETWORK INTENSITY" represents the fraction of workers with access to an internal network (leased lines or frame relays) in the three-digit industry across all countries. "NETWORK Price" is the cost of an annual subscription to a leased line contract at 2006 PPP USD (taken from the OECD *Telecommunication Handbook*, 2007). Regressions weighted by the plant's share of firm employment.

TABLE 7 - ROBUSTNESS CHECKS

	(1) Baseline	(2) Regional dummies and Lerner index	(3) Additional firm level controls	(4) Alternative NETWORK (LAN/WAN)	(5) Alternative construction of ICT variables	(6) Include Management quality	(7) Alternative dependent variable	(8) Drop size controls	(9) Condition on industries with at least 3 firms
Panel A: Plant Manager Autonomy									
ERP	0.116**	0.096*	0.112**	0.114**	0.118**	0.119**	0.133**	0.125**	0.113**
	(0.054)	(0.052)	(0.054)	(0.053)	(0.053)	(0.054)	(0.059)	(0.054)	(0.056)
NETWORK	-0.110**	-0.127**	-0.098*	-0.134**	-0.125**	-0.112**	-0.099*	-0.115**	-0.134**
	(0.053)	(0.052)	(0.053)	(0.063)	(0.051)	(0.053)	(0.056)	(0.054)	(0.055)
Observations	3,434	3,434	3,434	3,434	3,434	3,434	3,434	3,434	3,149
Firms	948	948	948	948	948	948	948	948	870
Panel B: Workers' Autonomy									
CAD/CAM	0.535*	0.650**	0.566**	0.641**	0.458	0.492*	0.863**	0.534*	0.441*
	(0.274)	(0.284)	(0.285)	(0.268)	(0.280)	(0.275)	(0.342)	(0.277)	(0.263)
	[0.053]	[0.049]	[0.054]	[0.061]	[0.065]	[0.049]	[0.242]	[0.054]	[0.037]
NETWORK	-0.226	-0.402*	-0.236	-0.659***	-0.230	-0.263	-0.090	-0.227	-0.215
	(0.180)	(0.211)	(0.190)	(0.249)	(0.174)	(0.184)	(0.217)	(0.181)	(0.184)
	[-0.023]	[-0.03]	[-0.022]	[-0.063]	[-0.021]	[-0.026]	[-0.017]	[-0.023]	[-0.018]
Observations	874	874	874	874	874	874	874	874	837
Firms	534	534	534	534	534	534	534	534	516
Panel C: Plant Manager Span of Control									
CAD/CAM	0.155**	0.208***	0.157**	0.153**	0.156**	0.156**		0.167**	0.152*
	(0.075)	(0.075)	(0.075)	(0.075)	(0.074)	(0.074)		(0.074)	(0.079)
NETWORK	0.053	0.045	0.030	0.069	0.048	0.035		0.052	0.025
	(0.041)	(0.042)	(0.041)	(0.058)	(0.040)	(0.041)		(0.042)	(0.042)
Observations	1,415	1,415	1,415	1,415	1,415	1,415		1,415	1,251
Firms	859	859	859	859	859	859		859	781

Notes: * = significant at the 10%, ** = 5%, ***= 1%. Panel A and C estimated by OLS. Panel B is estimated by probit with standard errors in parentheses and marginal effects (evaluated at the mean) in square brackets. Standard errors are clustered by firm in all columns. sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). All columns exclude firms where the plant manager is the CEO and include a dummy equal to unity if the CEO is on site. All columns include noise controls, firm controls and industry dummies as in previous tables. "ERP" = Enterprise Resource Planning, "NETWORK" = firm has an internal network (leased lines or frame relays) and "CAD/CAM" = Computer Assisted Design or Manufacturing. In column (2) regional (NUTS2) dummies and the inverse of the Lerner index are included as additional controls. In column (3) the ln(capital/employment ratio), ln(sales/employment ratio), ln(average wages), ln(global ultimate owner employment), ln(firm age) and a publicly listed dummy are included as additional controls. In column (4) the network variable denotes the presence of LAN/WAN systems. In column (5) we construct the ICT variables as equal to unity if there is a positive value in any plant. In column (6) the average management score (computed across the 18 management questions in Bloom and Van Reenen, 2007) is included as additional control. In column (7) the dependent variable is the principal factor component of the four different Plant Manager Autonomy questions (Panel A) and a dummy equal to unity if the pace of work question takes values above three (Panel B). In column (8) we drop firm and plant size from the regressions. Column (9) conditions on having at least three firms per three digit industry.

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APPENDICES

A Appendix A: Proofs

Recall the value of a firm with three layers is $\pi^* = \max_{z_p,x_m} 1-(a_p z_p + w_p) - (a_m + a_m x_m + w_m)h(1-F(z_p)) - (a_c + w_c)h^2(1-F(z_p))(1-G(x_m))$. To show proposition 2, first take first order conditions with respect to the two types of decisions, z_p and x_m. These are:

$$\begin{aligned} foc_{z_p} &: -a_p + ((a_m + a_m x_m + w_m) + (a_c + w_c)h(1-G(x_m)))\, hf(z_p) = 0 \\ foc_{x_m} &: [-a_m + (a_c + w_c)hg(x_m))]h(1-F(z_p)) = 0 \end{aligned}$$

To sign the Hessian, note first that the second cross derivatives are 0 at the optimum. To see this take the second order condition

$$\frac{\partial foc_{x_m}}{\partial z_p} = [a_m - (a_c + w_c)hg(x_m))]hf(z_p)$$

Optimality when managers are used requires that $[-a_m + (a_c + w_c)hg(x_m))] = 0$ (since $F(z_p) < 1$ or else workers work on their own as they know everything), and thus the Hessian is:

$$H = \begin{pmatrix} ((a_m + a_m x_m + w_m) + (a_c + w_c)h(1-G(x_m))\, hf'(z_p) & 0 \\ 0 & h(a_c + w_c)g'(x_m) \end{pmatrix}$$

Since $f'(z_p) < 0$ and $g'(x_m) < 0$ (management by exception– those higher up specialized in exceptions), the solution of the first order conditions is a local optimum. Letting the vector foc= $(foc_{z_p} foc_{x_m})$:

$$\begin{aligned} \frac{\partial foc}{\partial c_p} &= \begin{pmatrix} -1 \\ 0 \end{pmatrix}; \qquad \frac{\partial foc}{\partial c_m} = \begin{pmatrix} h(1+x_m)f(z_p) \\ -1 \end{pmatrix}; \\ \frac{\partial foc}{\partial h} &= \begin{pmatrix} ((a_m + a_m x_m + w_m) + 2h(a_c + w_c)(1-G(x_m))\, f(z_p) \\ (a_c + w_c)g(x_m) \end{pmatrix} \end{aligned}$$

Let the vector $vars = (z_p\ x_m)$ .Then for each parameter, $\frac{\partial vars}{\partial t} = -H^{-1}\frac{\partial foc}{\partial t}$ gives:

$$sign\begin{pmatrix} \frac{\partial z_p}{\partial a_p} \\ \frac{\partial x_m}{\partial a_p} \end{pmatrix} = \begin{pmatrix} <0 \\ 0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial z_p}{\partial a_m} \\ \frac{\partial x_m}{\partial a_m} \end{pmatrix} = \begin{pmatrix} >0 \\ <0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial z_p}{\partial h} \\ \frac{\partial x_m}{\partial h} \end{pmatrix} = \begin{pmatrix} >0 \\ >0 \end{pmatrix}.$$

For the effects in span, simply note that the span of control of corporate managers is $s_c = n_m/n_c = 1/\left((1-G(x_m))h\right)$ and that of middle managers: $s_m = N/n_m = 1/\left((1-F(z_p)h\right)$,

$$sign\begin{pmatrix} \frac{\partial s_m}{\partial a_p} \\ \frac{\partial s_c}{\partial a_p} \end{pmatrix} = \begin{pmatrix} <0 \\ 0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial s_m}{\partial a_m} \\ \frac{\partial s_c}{\partial a_m} \end{pmatrix} = \begin{pmatrix} >0 \\ <0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial s_m}{\partial h} \\ \frac{\partial s_c}{\partial h} \end{pmatrix} = \begin{pmatrix} \lessgtr 0 \\ \lessgtr 0 \end{pmatrix}.$$

To get the table in the paper, note that the predictions are with respect to a *fall* in these costs and thus all of the signs must be reversed to obtain the prediction.

Finally, note also that if we let a_m be also the acquisition cost of CEOs, so that ERP affects both CEOs and plant managers equally nothing changes (as the proposition states), so that $a_c = a_m$. The first foc becomes $foc_{z_p} : -a_p + ((a_m + a_m x_m + w_m) + (a_m + w_c)h(1 - G(x_m))\, hf(z_p)$, foc_{x_m} changes to: $-a_m + (a_m + w_c)hg(x_m))$, and

$$\frac{\partial foc}{\partial a_m} = \begin{pmatrix} ((1 + x_m) + h(1 - G(x_m))\, hf(z_p) > 0 \\ -1 + hg(x_m) = -w_c hg(x_m)/a_m < 0 \end{pmatrix}$$

so that $\text{sign}\begin{pmatrix} \frac{\partial z_p}{\partial a_m} \\ \frac{\partial x_m}{\partial a_m} \end{pmatrix} = \begin{pmatrix} >0 \\ <0 \end{pmatrix}$ is still true.

B Appendix B: Survey of IT Managers on the Impact of ERP

In the Summer and Fall of 2008 Kretschmer and Mahr (2009) conducted a survey of IT managers in medium-sized (100 to 5,000 employees) German and Polish firms that were randomly chosen from the population of manufacturing firms. The aims of the survey were wider than just ERP and collected information on management and other factors. At our request some questions on the use of ERPwere inserted. Answers to the questions where on a Likert Scale from 1 = strongly disagree to 5 = strongly agree. The key questions for our purposes were the following:

Q21 "Our ERP system is used to endow top management with more and better information"

Q24 "Our ERP system is used to endow middle managers with more and better information"

Q23 "Our ERP system is used to faster communicate information and directives from top management to employees"

Q26 "Our ERP system is used to faster communicate information and directives from middle management to employees"

Figure 5 shows the distribution of answers to these questions. It is clear from this figure that most respondents were likely (a "4") or very likely (a "5") to agree with statements Q21 and Q24 suggesting ERP was related to information acquisition. By contrast, as many people disagreed as agreed with the statements in Q23 and Q26 that ERP lowers communication costs. The mean of the information question is 3.8 for Q24 and 4.03 for Q21 whereas for the communication question it is 2.76 for Q23 and 2.71 for Q26.

Table A1 shows regression versions of these descriptive statistics. Likert scales between respondents can be biased because each respondent implicitly has a different scaling when they answer such questions (Manski, 2004). We can deal with this by only comparing "within respondent", i.e. looking at the relative responses for the same individual across questions. We construct several such variables, but the key one is "DIF1" the absolute difference between "Our ERP system is used to endow middle managers with more and better information" (Q24) and "Our ERP system is used to faster communicate information and directives from top management to employees" (Q23). This is an index from -4 to 4 indicating the degree to which ERP reduces information costs relative to communication costs. A positive value

of this index indicates that managers are more likely to view *ERP* as improving information costs rather than reducing communication costs.

Column (1) of Table A1 shows that the mean value of this index is just above one and that this is a significant difference. This is consistent with our assumption that ERP is used more as an information acquisition tool than a communication tool. We condition on some confounding influences - country dummies, industry dummies and size in column (2) which shows the difference is robust. One might be concerned that the communication question relates to top managers, so we also used "DIF2" which keeps the information question the same (Q21) but deducts "Our ERP system is used to faster communicate information and directives from middle management to employees" (Q26). The results of using this as a dependent variable are in column (3) which are almost identical to column (2). Finally we checked whether ERP is better at endowing top management with more information than middle management by constructing "DIF3" the absolute difference between "Our ERP system is used to endow middle managers with more and better information" (Q24) and "Our ERP system is used to endow top management with more and better information" (Q21). This difference is positive but completely insignificant. In terms of our theory this means that ERP shifts a_m downwards to a similar extent as a_c which is again, what we assumed for our interpretation of the empirical results[41]. See Kretschmer and Mahr (2009) for full details on the underlying survey.

C Appendix C: Data Appendix

C.1 CEP Management and Innovation Survey Dataset

C.1.1 The Survey Sampling Frame

We use a sub-set of the CEP Management and Organization survey in this paper (see Bloom, Sadun and Van Reenen, 2008, for full details of larger sample) where we have ICT data (see below). Our sampling frame was based on the Bureau van Dijk (BVD) Amadeus dataset for Europe (France, Germany, Italy, Poland, Portugal, Sweden and the U.K.) and Icarus for the US. These databases all provide sufficient information on companies to conduct a stratified telephone survey (company name, address and a size indicator). These databases also typically have some accounting information, such employment, sales of capital assets. Apart from size, we did not insist on having accounting information to form the sampling population, however.

Amadeus is constructed from a range of sources, primarily the National registries of companies (such as Companies House in the UK). Icarus is constructed from the Dun & Bradstreet database, which is a private database of over 5 million US trading locations built up from credit records, business telephone directories and direct research. In every country the sampling frame was all firms with a manufacturing primary industry code with between 100 and 5,000 employees on average over the most recent three years of data (typically 2002 to 2004)[42].

Interviewers were each given a randomly selected list of firms from the sampling frame. This should therefore be representative of medium sized manufacturing firms. The size of the sampling frame appears broadly proportional to the absolute size of each country's manufacturing base, the US, has the most firms and Sweden and Portugal the least[43]. In addition to randomly surveying from the sampling frame described above we also tried to resurvey the firms we interviewed in the 2004 survey wave used in Bloom and Van Reenen (2007). This was a sample of 732 firms from France, Germany, the UK and the US, with a manufacturing

[41] There are differences in the comparative statistcs if *ERP* or another technology reduced c_c but not c_m.

[42] In the US only the most recent year of employment is provided. In Portugal the population of firms with 100 to 5000 employees was only 242, so we supplemented this with the 72 firms with 75 to 100 employees. We checked the results by conditioning on common size bands (above 150 in all countries).

[43] The size of the manufacturing sector can be obtained from http://laborsta.ilo.org/, a database maintained by ILO.

primary industry code and 50 to 10,000 employees (on average between 2000 and 2003). This sample was drawn from the Amadeus dataset for Europe and the Compustat dataset for the U.S. Only companies with accounting data were selected[44]. As a robustness test we also drop the firms that were resurveyed from 2004.

C.1.2 Sample Representativeness

Comparing the aggregate number of employees for different size bands from our sampling frame with the figures for the corresponding manufacturing populations in each of the countries (obtained from national census data), we find that in all countries but two the sampling frame broadly matches up with the population of medium sized manufacturing firms. This suggests our sampling frame covers the population of all firms. In Germany and Portugal the coverage is less complete as the frame appears to cover around a third of manufacturing employees. To address this problem we always include country fixed-effects to try to control for any differences across countries. Second, we control for size and industry. This should help to condition out some of the factors that lead to under/over sampling of firms. Finally, we made sure the results were robust to dropping Germany and Portugal.

45% of the firms we contacted took part in the survey: a high success rate given the voluntary nature of participation. Of the remaining firms 17% refused to be surveyed, while the remaining 38% were in the process of being scheduled when the survey ended. The decisions to reject the interview is uncorrelated with revenues per worker, listing status of the firm or firm age. Large firms and multinationals were more likely to respond although the magnitude of this effect is small (e.g. multinationals were about 7% more likely to agree to the interview and firms about 4 percentage points more likely for a doubling in size). European firms were slightly more likely to respond than US firms.

C.2 Harte Hanks Data

The ICT data used is constructed using the Ci Technology Database (CiDB) produced by the international marketing and information company Harte Hanks (HH). Harte-Hanks is a NYSE listed multinational that collects IT data primarily for the purpose of selling on to large producers and suppliers of IT products (e.g. IBM, Dell etc). Their data is collected for over 160,000 plants across 20 European countries, and another 250,000 across the US. The US branch has the longest history with the company beginning its data collection activities in the mid 1980s.

Harte Hanks surveys plants (referred to as "sites" in the CiTB database) on a rolling basis with an average of 11 months between surveys. This means that at any given time, the data provides a "snapshot" of the stock of a firm's IT. The CiTDB contains detailed hardware, equipment and software information at the plant level. Areas covered by the survey include PCs, many types of software, servers, storage and IT staff (including development staff such as programmers). The fact that HH sells this data on to major firms like IBM and Cisco, who use this to target their sales efforts, exerts a strong market discipline on the data quality. If there were major discrepancies in the collected data this would rapidly be picked up by HH's clients when they placed sales calls using the survey data, and would obviously be a severe problem for HH future sales[45]. Because of this HH run extensive internal random quality checks on its own data, enabling them to ensure high levels of data accuracy.

[44] So, for the UK and France this sampling frame was very similar to the 2006 sampling frame. For Germany it is more heavily skewed towards publicly quoted firms since smaller privately held firms do not report balance sheet information. For the US it comprised only publicly quoted firms. As a result when we present results we always include controls for firm size.

[45] HH also refunds data-purchases for any samples with error levels above 5%.

Another valuable feature of the CiDB is its consistency of collection across countries. The data for Europe is collected via a central call centre in Dublin and this ensures that all variables are defined on an identical basis across countries. This provides some advantages over alternative strategies such as (for example) harmonizing government statistical register data collected by independent national agencies.

HH samples all firms with over 100 employees in each country. Thus, we do lose smaller firms, but since we focus on manufacturing the majority of employees are in these larger firms. It is also worth noting this survey frame is based on firm employment - rather than plant employment - so the data contains plants with less than 100 employees in firms with multiple plants. Furthermore, HH only drops plants from the survey if they die or repeatedly refuse to answer over several years, so that the sampling frame covers all firms that have had at 100 employees in any year since the survey began. In terms of survey response rate HH reports that for the large European countries (UK, France, Germany, Italy, and Spain) they had a response rate of 37.2% in 2004 for firms with 100 or more employees. Bloom, Draca and Van Reenen (2010) provide further information on the HH dataset.

C.3 Firm level accounting data

Our firm accounting data on sales, employment, capital, profits, shareholder equity, long-term debt, market values (for quoted firms) and wages (where available) came from Amadeus dataset for Europe (France, Germany, Italy, Poland, Portugal, Sweden and the U.K.) and on Icarus for the US

C.4 Leased Line Data

The data on cross national prices is given by OECD (2007). Although European prices have been falling over the past decade due to liberalizations and pressures from the regulators (e.g. European Commission DG-Competition), there remains considerable concern about differential degrees of competition and regulation generating cross-national price disparities. "Local leased line prices remain of concern where there is insufficient competition. For users in these areas this means that incumbents can continue to charge prices that are not disciplined by competition. For new entrants it means that incumbents may price local leased circuits in an anti-competitive manner" (OECD Communication Outlook, 2005).

"Leased lines are provided by traditional telecom operators. New market entrants have their own networks but need to link their customers' premises to it. This link is called a 'leased line part circuit' and is usually provided by the incumbent. The availability at the wholesale level of these links at reasonable prices is a necessary condition for a competitive leased lines retail market and for pro-competitive downstream 'knock-on' effects" (European Commission Report, 2002)

A major turning point in the pricing of leased lines took place in 1998 when a significant number of European countries fully liberalized their telecommunication markets. The impact of increasing liberalization is evident in the OECD's Index of leased line prices. At the distances of 50 and 200 kilometers the leased lines (2Mbit/s) index fell from 77 in 1997 to 31 by 2004. This process happened at a much faster rate in some countries than others (see OECD, 2005).

TABLE A1 - ERP SURVEY: THE IMPACT OF ERP IS MORE ON INFORMATION COSTS THAN ON COMMUNICATION COSTS

	(1)	(2)	(3)	(4)
Dependent Variable	**DIF1**	**DIF1**	**DIF2**	**DIF3**
Constant	1.074***	1.068**	1.042**	0.102
	(0.060)	(0.512)	(0.496)	(0.383)
Firms	431	431	431	431
Country controls	No	Yes	Yes	Yes
Industry controls	No	Yes	Yes	Yes
Employment controls	No	Yes	Yes	Yes

Notes: Countries are Germany and Poland (Kretschmer and Mahr, 2009). Estimation by OLS. Robust standard errors below coefficients. Industry controls are three digit employment. Questions are on a 1 to 7 Lickert Scale from strongly disagree (1) to strongly agree (5).

Q21 "Our ERP system is used to endow top management with more and better information"
Q24 "Our ERP system is used to endow (middle) managers with more and better information"
Q23 "Our ERP system is used to faster communicate information and directives from top management to employees"
Q26 "Our ERP system is used to faster communicate information and directives from (middle) management to employees"

Definitions of dependent variable:
DIF1 = Q24 – Q23
DIF2 = Q24 – Q26
DIF3 = Q24 - Q21

So DIF1, for example is the absolute difference between "ERP endows middle management with better information" less "ERP is used to faster communicate information and directives from top management to employees". This is an index from -4 to 4 indicating the degree to which ERP reduces information costs relative to communication costs. A positive value of this index indicates that managers are more likely to view ERP as improving information costs rather than reducing communication costs.

TABLE A2: DETAILS OF THE DECENTRALIZATION SURVEY QUESTIONS

For Questions D1, D3 and D4 any score can be given, but the scoring guide is only provided for scores of 1, 3 and 5.

Question D1: *"To hire a FULL-TIME PERMANENT SHOPFLOOR worker what agreement would your plant need from CHQ (Central Head Quarters)?"*

Probe until you can accurately score the question – for example if they say "*It is my decision, but I need sign-off from corporate HQ.*" ask "*How often would sign-off be given?*"

	Score 1	Score 3	Score 5
Scoring grid:	No authority – even for replacement hires	Requires sign-off from CHQ based on the business case. Typically agreed (i.e. about 80% or 90% of the time).	Complete authority – it is my decision entirely

Question D2: *"What is the largest CAPITAL INVESTMENT your plant could make without prior authorization from CHQ?"*

Notes: (a) Ignore form-filling

(b) Please cross check any zero response by asking "*What about buying a new computer – would that be possible?"*, and then probe….

(c) Challenge any very large numbers (e.g. >$¼m in US) by asking "*To confirm your plant could spend $X on a new piece of equipment without prior clearance from CHQ?*"

(d) Use the national currency and do not omit zeros (i.e. for a US firm twenty thousand dollars would be 20000).

Question D3: *"Where are decisions taken on new product introductions – at the plant, at the CHQ or both"*?

Probe until you can accurately score the question – for example if they say "*It is complex, we both play a role* "ask "*Could you talk me through the process for a recent product innovation?*"

	Score 1	Score 3	Score 5
Scoring grid:	All new product introduction decisions are taken at the CHQ	New product introductions are jointly determined by the plant and CHQ	All new product introduction decisions taken at the plant level

Question D4: *"How much of sales and marketing is carried out at the plant level (rather than at the CHQ)"*?

Probe until you can accurately score the question. Also take an average score for sales and marketing if they are taken at different levels.

	Score 1	Score 3	Score 5
Scoring grid:	None – sales and marketing is all run by CHQ	Sales and marketing decisions are split between the plant and CHQ	The plant runs all sales and marketing

Question D5: *"Is the CHQ on the site being interviewed"*?

Question D6: "How much do managers decide how tasks are allocated across workers in their teams"

	Score 1	Score 2	Score 3	Score 4	Score 5
Interviewers are read out the following five options, with our scoring for these note above:	All managers	Mostly managers	About equal	Mostly workers	All workers

Question D7: "Who decides the pace of work on the shopfloor"

	Score 1	Score 2	Score 3	Score 4	Score 5
Interviewers are read out the following five options, with "customer demand" an additional not read-out option	All managers	Mostly managers	About equal	Mostly workers	All workers

Question D8: "How many people directly report to the PLANT MANAGER (i.e. the number of people the PLANT MANAGER manages directly in the hierarchy below him)? Note: cross-check answers of X above 20 by asking "So you directly manage on a daily basis X people?"

Notes: The electronic survey, training materials and survey video footage are available on http://cep.lse.ac.uk/management/default.asp

TABLE A3 – EXTENDED THEORY PREDICTIONS

		(1) Plant Manager Autonomy (x_m)	(2) Worker Autonomy (z_p)	(3) Plant Manager Span of Control (s_m)	(4) CEO Span of Control (s_c)
Reduction in communication costs *(h)*	*Technology Indicator*	*NETWORK (h)*	*NETWORK (h)*	*NETWORK (h)*	*NETWORK (h)*
	Theoretical Prediction	-	-	*?*	*?*
Reduction in information acquisition costs for non-production decisions *(a_m)*	*Technology Indicator*	*ERP (a_m)*	*ERP (a_m)*	*ERP (a_m)*	*ERP (a_m)*
	Theoretical Prediction	+	-	-	+
Reduction in information acquisition costs for production decisions *(a_p)*	*Technology Indicator*	*CAD/CAM (a_p)*	*CAD/CAM (a_p)*	*CAD/CAM (a_p)*	*CAD/CAM (a_p)*
	Theoretical Prediction	*0*	+	+	*0*

Notes: ERP denotes Enterprise Resource Planning, *CAD/CAM* denotes Computer Assisted Design/Computer Assisted Manufacturing and *NETWORK* denotes the presence of a network (leased line/frame relay). A "+" denotes an increase, a "-'' a decrease a "0" denotes no effect and "?'' denotes an ambiguous sign.

TABLE A4 – CROSS EFFECTS OF TECHNOLOGIES

Dependent Variable	(1) Plant Manager Autonomy	(2) Workers' Autonomy	(3) Ln(PM Span)
NETWORK	-0.111**	-0.228	0.020
	(0.053)	(0.180)	(0.054)
		[-0.023]	
CAD/CAM	0.091	0.532*	0.156**
	(0.223)	(0.275)	(0.076)
		[0.053]	
ERP	0.116**	-0.290	0.053
	(0.054)	(0.177)	(0.043)
		[-0.029]	
Number of Observations	3,434	874	1,415
Number of Firms	948	534	859

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. Rows correspond to separate regressions based on final most general specifications in Tables 3 - 5. All equations estimated by OLS except Worker autonomy equation which is estimated by probit ML with marginal effects (evaluated at the mean) in square brackets. Standard errors are robust and clustered by firm. The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). ERP" denotes Enterprise Resource Planning, "NETWORK" denotes the firm has an internal network (leased lines or frame relays) and "CAD/CAM" denotes Computer Assisted Design or Manufacturing software.

TABLE A5 – CEO SPAN OF CONTROL

	(1)	(2)	(3)
Dependent Variable		**CEO Span of Control**	
ERP	0.235***		0.217**
	(0.086)		(0.087)
	[0.082]		[0.075]
NETWORK		0.256***	0.239***
		(0.090)	(0.091)
		[0.089]	[0.083]
Ln(Percentage College)	0.103*	0.107*	0.108**
	(0.055)	(0.055)	(0.055)
	[0.036]	[0.037]	[0.037]
ln(COMPUTERS/Employee)	-0.125**	-0.130**	-0.148**
	(0.057)	(0.058)	(0.058)
	[-0.044]	[-0.045]	[-0.051]
ln(Firm Employment)	0.288***	0.276***	0.278***
	(0.073)	(0.073)	(0.073)
	[0.100]	[0.096]	[0.097]
Plant Employment	-0.500***	-0.492***	-0.500***
	(0.101)	(0.101)	(0.101)
	[-0.174]	[-0.171]	[-0.174]
Number of Observations	3,861	3,861	3,861
Number of Firms	1,059	1,059	1,059

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. The dependent variable in all columns is a dummy equal to one if the firm reports more than one production plant. All columns are estimated by probit ML with standard errors in parentheses (robust and clustered by firm). Marginal effects (evaluated at the mean) reported in square brackets. The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). All columns contain the same controls in Table 3-5 "ERP" denotes Enterprise Resource Planning and "NETWORK" denotes the firm has an internal network system (leased lines or frame relays). The time period covered by the ICT variables is 2001-2006 (year dummies included).

TABLE A6 - CONTROLLING FOR CONTINGENT PAY

Dependent Variable	(1) Plant Manager Autonomy	(2) Workers' Autonomy	(3) Ln(Plant Manager Span)	(4) Plant Manager Autonomy	(5) Workers' Autonomy	(6) Ln(Plant Manager Span)
ERP	0.115**			0.114**		
	(0.054)			(0.054)		
CAD/CAM		0.555**	0.158**		0.556**	0.156**
		(0.265)	(0.076)		(0.274)	(0.075)
		[0.056]			[0.053]	
NETWORK	-0.110**	-0.221	0.053	-0.109**	-0.227	0.048
	(0.053)	(0.179)	(0.043)	(0.053)	(0.181)	(0.042)
		[-0.022]			[-0.021]	
Bonus as a % of Total Salary	0.478**	-0.260	0.086			
For typical manager	(0.235)	(0.727)	(0.141)			
		[-0.026]				
% Salary Increase on Promotion				-0.025	0.479	0.168
For a typical manager				(0.220)	(0.597)	(0.131)
					[0.045]	
Number of Observations	3,434	874	1,415	3,434	874	1,415
Number of Firms	948	534	859	948	534	859

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. All columns estimated by OLS except columns 2 and 5 which are estimated by probit ML with standard errors in parentheses and marginal effects (evaluated at the mean) in square brackets. Standard errors are robust and clustered by firm in all columns. The sample includes firms based in France, Germany, Italy, Portugal, Poland, Sweden, the UK and the US (country dummies included). All columns include the same controls as Table 3 through 5. "ERP" denotes Enterprise Resource Planning, "NETWORK" denotes the firm has an internal network (leased lines or frame relays) and "CAD/CAM" denotes Computer Assisted Design or Manufacturing software.