The distinct effects of Information Technology and Communication Technology on firm organization*

Nicholas Bloom†, Luis Garicano ‡, Raffaella Sadun§ and John Van Reenen¶

April 17, 2009

Abstract

Empirical studies on information communication technologies (ICT) typically aggregate the 'information' and 'communication' components together. We show theoretically and empirically that these have very different effects on the empowerment of employees, and therefore on wage inequality and productivity. If manangement layers are devices to acquire and transmit knowledge and information, we expect technologies that reduce information costs to enable agents to acquire more knowledge and 'empower' lower level agents. Conversely, technologies enabling communication substitute agent's knowledge for directions from their managers, and will lead to the centralization of decision making. Using an original dataset of firms in the US and seven European countries we study the impact of ICT on worker autonomy, plant manager autonomy and spans of control. Consistently with the theory we find that better information technologies (Enterprise Resource Planning for plant managers and CAD/CAM for production workers) increase autonomy and widen the span of control. By contrast, communication technologies (like data networks) decrease autonomy for both workers and plant managers. Our findings are robust to using exogenous variation in cross-country telecommunication costs arising from differential regulatory regimes.

JEL No. O31, O32, O33, F23

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

*We would like to thank the ESRC for help with financing this research at the Centre for Economic Performance. We thank Oriana Bandeira, Steven Pischke, Andrea Prat and participants at the LSE Labor workshop at the NBER Summer Institute in Labor and Personnel Economics and at the Harvard/MIT workshop in Organizational Economics for their useful comments.

†Stanford University

‡London School of Economics and Centre for Economic Performance

§London School of Economics and Centre for Economic Performance

¶London School of Economics and Centre for Economic Performance

1 Introduction

Most studies of the impact of information and communication technologies (ICT) on firm organization, inequality and productivity 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 is becoming cheaper to access. Second, through the spread of cheap wired (IP-based) and wireless communications, agents find it easier to communicate with each other (e.g. e-mail and mobile phones). These two distinct changes can be expected to have a very different impact on firm organization. While cheaper communication technology generates a reduction in the variety of tasks performed by workers as agents can specialize further and 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, but also in the labor market, as information access and communication technology changes can be expected to affect the wage distribution in opposite directions. In this paper, we utilize a new international firm-level dataset 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. A decision is a solution to a problem and making decisions requires acquiring the relevant knowledge. 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 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 on communication costs: trading-off knowing versus asking for directions.

The level at which decisions are taken 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 thus make 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 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 CHQ 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 2, 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. 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 has taken place reducing the cost for workers of being informed: Computer Assisted Design/Computer Assisted Manufacturing (CAD/CAM). A worker with access to those machines 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, the span of control of plant managers.

On the other hand, as we argued above, we expect communication technologies to centralized decision making. This will be true both for production workers (so that plant-managers will make more of their decisions), and also for plant-managers (so that the CHQ will take more of their decisions). A key technological innovation affecting communication is the growth of networks and connectedness. 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 dataset 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; Bloom, Sadun and Van Reenen, 2008) 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 for hardware 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 simple conditional correlations between the different ICT measures and four dimensions of the organization of the firm, guided by our theoretical predictions. But we also 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 in networks are at a greater disadvantage in countries with high communication costs and use this to identify the effect of communication costs on centralization.

In short, we find evidence that is broadly 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 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).

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. As noted above, this is highly problematic as such 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[1]. A second branch tries to endogenize organization, but does not discriminate between types of ICT[2]. 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[3]. 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, Lavy and Murnane, 2003) or the result of coordination issues (Cremer et al. 2007 and Alonso et al, 2008). Although we are not rejecting the 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[4].

We proceed as follows. We first discuss in Section 2 the key technological changes in production affecting information and communication costs. We then propose a basic theoretical framework and suggest its implications in our context (Section 3). We then discuss our data (Section 4), empirical modelling strategy (Section 5) and present our results (Section 6). The final section offers some concluding comments.

2 Technological changes in Information and Communication Costs

In this section we study three key technical changes: the introduction of intranets ($NETWORK$); 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.[5]The reason we focus on these technologies is that they are major advances in the manufacturing sector that we study and second, we believe they map clearly into reductions in

[1] 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).

[2] For example see Acemoglu, Aghion, Lelarge, Van Reenen and Zilibotti (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.

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

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

[5] We thank software engineers at Sun Microsystems and EDS/HP and consultants at McKinsey and Accenture for many useful discussions that shaped our thinking on these matters.

communication costs ($NETWORK$) and reductions in information acquisition costs for non-production decisions (ERP) and production decisions (CAD/CAM).

2.1 The Rise of Intranets: Facilitating Communication through the Organization.

Over the last thirty years firms have experienced substantial falls in communication costs. Probably the key change over the last decade has been the introduction of corporate intranets. These allow companies to connect all the plants to corporate headquarters, reducing the cost of communication between headquarters and local managers. In the past, for example, sharing documentation with headquarters required the use of fax or mail. This high communication costs made real-time production control from the CHQ impossible, effectively delegating day-to-day control of the plant to local management. Once the leased-lines and corporate intranet is installed, the cost of communication between local and central managers is reduced. This allows for the use of more experienced central management to spot the signs of production problems - for example identifying specific types of output variations as fault indicators - and providing 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.

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

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/CAM resulted in important changes in this process. The CAD part of the CAD/CAM software allows the plant to directly implement the initial design stage for modifications of standard products, and the CAM enables this team to program up the Computer Numerical Control equipment to produce the key parts.[6]

In this way, *CAD/CAM* has revolutionized manufacturing. Essentially, it 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 CHQ engineering team.

2.3 Connected Real Time Data bases: Increasing Managerial Information

Enterprise Resource Planning (*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.[7]

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 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 headquarters are integrated in the company-wide *ERP* system, plant managers and the CHQ would have a full company-level overview of production, inventory, orders and finance across the company. The parallels with coordination across multiple stores in a big retail chain are apparent.

[6] 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). Major players in the *CADCAM* supply industry are UGS Corp (owned by Siemens), Dassault Systèmes and Hitachi Zosen.

[7] 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.

Thus 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. By improving the access of managers to local time information it allows them to make better decisions. Indeed, in a study of 163 large companies (Davenport et al, 2002) found that managers reported that the main benefit sought by firms in implementing ERP was "better managerial decision making:" Moreover, 63% of the companies reported they had achieved better decision making as a benefit of ERP. We further discuss (with the help of some data we collected) the role of ERP and how it maps into information access after discussing the theory.

To sum up, three important technological changes that have been observed in manufacturing have been as follows:

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

In what follows, we set up a simple model of a hierarchy that is involved in acquiring and using information in order to develop some hypothesis on the impact of information and communication technology on the organization of firms.

3 Theory: Communication, Information Access and Organization

3.1 The trade-off Between Communication and Information Access

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

Each production worker draws a unit measure of problems (or tasks or problems) 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. Problems are distributed according to a density function $f(z)$. Without loss of generality, we reorder problems so that $f'(z) < 0$, i.e. more common problems have a lower index. Agents can only deal with a problem or task if they have the relevant knowledge. For an agent i to learn to solve all tasks costs c_i. This cost may depend on technology available to different agents and their skill. Then an agent who learns all the tasks produces $1 - c_i$.[8] The cost of training agents can be reduced through a hierarchy in which production agents only learn to deal with the most common problems, that is those in $(0, z_p)$, and ask for help on the rest (the 'exceptions') to an agent who is specialized in problem solving, whom we call m (for manager).[9] Figure 1 illustrates this task allocation.

[Figure 1 about here]

The cost of hierarchy is the time wasted as 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, paid a wage w_p, and n_m managers specialized in 'problem solving' or 'helping' and paid wage w_m is:[10]

$$\pi = N - N(c_p z_p + w_p) - n_m(c_m z_m + w_m)$$

that is, the z_p most common problems are learned by the N production workers. We assume that the learning technology is such that managers know all the tasks that workers also know, so that knowledge overlaps.[11] Since all tasks must be dealt with $z_m = 1$. Whenever production workers confront problems or decisions for which they do not have enough knowledge so that they need help, a communication cost h (for helping cost) must be incurred per question

[8] We'll assume the cost of learning is linear so that learning z problems costs cz. 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] This first model is a stylized version of the model in Garicano (2000). There, there are as many layers of problem solvers as necessary and agents can decide which problems to do and which ones not to do. It is there shown that the organization we set up (charaterized by 'management by exception') is optimal. Intuitively, if those lower in the hierarchy learnt less common 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 may be the case because the learning takes place on the job or because the process of learning involves learning the 'easy' tasks first. The assumption is without loss, as it is easy to see that all the comparative statics are unchanged if knowledge is non overlapping, so that managers learn what workers do not know, that is $1 - z_p$. The overlapping knowledge restriction seems more reasonable in our empirical application.

posed. This is a communication costs, since it is only incurred when the problem could not be solved at first and help must be sought. A production agent can deal with a fraction $F(z_p)$ of the tasks and passes on $(1 - F(z_p))$. Thus a manager spends times $(1 - F(z_p))h$ helping each production worker. Since there are N agents, the needed number of managers or problem solvers is $Nh(1 - F(z_p)) = n_m$. This determines a trade-off between what the agents below can do and how many managers are needed - the more skilled the lower level agents, the less managers are needed. Figure 2 provides an overview of the model.

The problem then of the hierarchy is to decide the size or span of the hierarchy and workers training to maximize profits per problem. Substituting for the span:

$$\pi^* = \max_{z_p} [N (1 - (c_p z_p + w_p) - h(1 - F(z_p)) (c_m + w_m))]$$

[Figure 2 about here]

The following comparative statics follow in mediately.

Proposition 1 *1. A drop in communications (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 ($c = c_m = c_p$), or one affecting only lower level agents, c_p, increases lower level autonomy (z_p) and increases managerial span of control, s (as less questions are asked).

3. A reduction in the cost of acquiring information by managers only (c_m) reduces lower level autonomy (z_p) and reduces span of control (workers ask more questions).

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 straightforwardly from the fact that $\frac{\partial^2\pi}{\partial z_p \partial h} > 0$. Second, letting $c_p = c_m = c$, we have that: $\frac{\partial^2\pi}{\partial z_p \partial c} < 0$ (), and similarly $\frac{\partial^2\pi}{\partial z_p \partial c_p} < 0$, if workers can learn cheaper they can learn more. Finally, $\frac{\partial^2\pi}{\partial z_p \partial c_m} > 0$; The changes in span follow straightforwardly from $s = N/n_m = 1/ (h(1 - F(z_p)))$.

Intuitively (1), higher communication cost raises the value of additional worker knowledge, since that reduces the amount of communication needed; (2) higher knowledge acquisition cost for all agents raises the value for workers to ask questions rather than acquiring the knowledge themselves (economizing on expensive knowledge acquisition); and (3) when technology used by managers to acquire knowledge improves, more managers can be hired per worker so that each worker can ask more questions and acquire less knowledge. Essentially, while communication cost reductions facilitate the reliance of specialists and decrease what each worker can do, reductions in the cost of acquiring information make learning easier and reduce the need to rely on specialized problem solvers for help with solutions.

3.2 Extension: Production and Non production Decisions

Middle managers perform two broadly different functions: 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. 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.

We extend the model in the simplest possible way next, by considering a multilayer hierarchy involving corporate managers, middle managers (in our data, plant managers) and production workers. The CHQ 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 c_p and middle managers at cost c_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 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 headquarters. 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 c_i; thus training middle managers to deal with non production problems costs $c_m x_m$, while, analogously to the production decision case, corporate managers can deal with all (a unit measure) of non-production problems at a cost c_c (c for corporate), with $c_c \gtrless c_m$. A hierarchy with n_m non-production problems with middle managers with 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:

$$\pi^* = \max_{z_p, x_m, n_m, n_c} N - (c_p z_p + w_p)N - (c_m + c_m x_m + w_m)n_m - (c_c + w_c)n_c \tag{1}$$

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 training them to deal with decisions $z < z_p$ ($c_p z_p$). The third term is the cost of n_m middle managers - their wage (w_m), and training them to deal with production problems (c_m) and with a fraction x_m of non-production problems. The cost of dealing with them is assumed to be the same as the technology that is available to the manager to deal with these problems is the same (this assumption can be weakened by assuming them different with the only cost being the extra notation) 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 (c_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 (1) through by N, note that the profit function is constant returns to scale in N):

$$\frac{\pi^*}{N} = \max_{z_p, x_m} 1 - (c_p z_p + w_p) - (c_m + c_m x_m + w_m)h(1-F(z_p)) - (c_c + w_c)h^2(1-F(z_p))(1-G(x_m)) \tag{2}$$

[12] We assume communication or helping cost h is the same for production and non-production decisions for simplicity since, we 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.

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 (c_p) leads to an increase in production workers autonomy (z_p) and in the span of control of middle managers ($s_m = N/n_m$).

3. A reduction in the cost of acquiring information either by middle managers (c_m) or by them and corporate managers (c_c and c_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 ($\not{s}_m$).

We show these results formally in Appendix A. The framework generate twelve comparative statics - the impact of three technological costs (c_p, c_m, h) on four organizational outcomes (x_m, z_p, s_m, s_c) and our most general econometric specification will examine all of these predictions. Data constraints however, mean that we have much more powerful tests of some of these predictions than others (e.g. we only have a crude measure of CEO span). Consequently, the baseline model focuses on a sub-set of six empirical tests in Table 1.

We consider the determinants of the three organizational design problems in the first column with respect to the change in communication costs in column (4). Falling communication costs (proxied by $NETWORKS$) have negative effects on autonomy and ambiguous effects on spans (each worker does more but will ask more question). We repeat the exercise for information costs in column (4). Falling information acquisition costs for non-production decisions (proxied by ERP) are predicted to raise autonomy for plant managers as they can do more. 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 workers are making more of their own decisions).

The intuition is broadly as in the previous section: better information access pushes decisions down, as it allows for better decentralized decision making without an undue cognitive burden to 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.

3.3 Alternative theoretical channels

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

3.3.1 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 facilitiate 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.* When we do this Table 10 by including measures of the importance of incentive pay, our key results appear robust to this extension.

3.3.2 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 a and the manager of tasks $1 - z_0 - a$. The impact of automation is to increase the number of tasks a 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. 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. Thus a worker does $z_0 - a$ 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 span of control remains unchanged as the number of tasks done by the manager $(1 - z_0)$ are unchanged. Our data allows our testing of this channel – 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 of the autonomy of 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.

3.3.3 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 a Alonso et al. (2008) type model.

The pure coordination story, however, where the main impact of the information and communication changes is to decrease coordination costs will be easy to tell apart from ours. First, these theories do not have implications for spans of control; in fact, if horizontal communication increases, we'll 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 ($NETWORK$)- they all reduce coordination costs, and thus they all result in the same impact on decentralization (larger) and on spans (ambiguous). Our data will allow us to differentiate this perspective from ours, since we expect to find different impacts of both channels.

4 Data

We use a new international micro dataset combining novel sources from the US and eight European countries. Our two main sources 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 Center for Economic Performance (CEP) at LSE 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 where we were able to match the organization data with ICT data from an independent database. Appendix C provides more information, 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[13]. 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% and the response rate was uncorrelated with firm performance. The interviews took an average of 45 minutes with the

[13] 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.

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 self-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 also asked four questions on plant manager autonomy. First, we asked how much capital investment a plant manager could undertake without prior authorization from the CHQ. 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 this from a score of one, defined as all decisions taken at the corporate headquarters to a five defined as complete power ("real authority") of the plant manager, and intermediate scores varying degrees of joint decision making. In Table B1 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 by practice to mean 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, but we also experiment with other weighting schemes and we also show what happens when the questions 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 A1 (questions D6 and D7). These questions are scaled on a one to five basis, with a five denoting workers have full control over the pace of work and allocation of tasks and a one denoting managers have full control. 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). 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 are 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 CEO span (since we did not interview the CEO). But we try to get a sense of senior management's (CEO) 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 establishment level ICT data panel taken from the European Ci Technology Database (CiDB) produced by the international marketing and information company Harte-Hanks (HH). HH is a multinational firm that collects detailed hardware and software information primarily for the purpose of selling on to large producers and suppliers of ICT. The fact that HH sells this data on to major firms like IBM and Cisco exerts a strong market discipline on the data quality. Major discrepancies in the data are likely to be rapidly picked up when HH customers' sales force placed calls using the survey data. Because of this HH conducts extensive internal random quality checks on its own data, enabling them to ensure high levels of data accuracy.

The HH data has been collected annually for over one million establishments across European countries since the late-1990s and earlier in the US. They target all firms with 100 or more employees, obtaining about a 45% response rate. We use the data only for the firms we matched to those in the management survey (i.e. in the US, France, Germany, Italy, Poland, Portugal, Sweden and the UK). These were matched through the names of the firms (with addresses and employment also used to ensure clean matches). Bresnahan et al (2002) and Brynjolfsson and Hitt (2003) have previously used the US HH data to match this to large publicly quoted firms in Compustat, while Beaudry, Doms and Lewis (2006) and Bloom, Draca and Van Reenen (2008) have used the complete panel of establishments in the US and Europe respectively. No one has combined the software data with information on organizational form in a single country, let alone internationally as we do here.

HH collects data on both hardware measures and on the software applications we are interested in. ICT hardware such as PCs simultaneously reduces information and communication costs so although we will utilize the hardware measures from HH as is common in the literature, we do not expect a clear result. Instead, we use their date on networks (for communication costs), Enterprise Resource Planning (ERP) for reducing information access costs for non-production decisions and CAD/CAM for reducing 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 establishment.

- HH distinguishes up to 17 distinct types of ERP: the market leader is SAP[14] but Oracle, IBM and many others all offer products in this space.

- Recall that CAD/CAM's are software tools that assist production workers, engineers and machinists in manufacturing in all phases of production (e.g. finishing, contour milling and roughing). HH defines this under "workstation applications".

- HH measures the presence of Leased Lines or Frame Relays ($NETWORK$). These are IT infrastructures used by businesses to connect offices or production sites. A leased line is a symmetric telecommunications line connecting two locations. It is sometimes known as a 'Private Circuit' or 'Data Line'.[15]

In terms of other technologies we considered using e-mail to capture communication costs, but e-mail is now so ubiquitous that there is little variation. We condition on PC intensity, but note its theoretical ambiguity. 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 similarlity of results when using this as an alternative proxy for networks.

4.2.1 Does ERP provide information or enable monitoring?

We have argued in Section 2 that ERP reduces information costs much more than communication costs, but this may be more contentious. To investigate this issue in more detail we

[14] For example, SAP's R/3 client/server version launched in 1992 replaced the older mainframe based R/2.

[15] 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.

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.

4.3 Other Data

In addition to the organization variable, the CEP survey also collected a wide variety of other variables such as the skills and demographics in the workplace 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. For the country data on network prices we use the cost of an annual subscription to a leased line contract at 2006 PPP US$ taken from the OECD (2007).

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 Strategy

5.1 Basic Model

Consider the following generic equation that we wish to estimate:

$$y^O_{ijk} = \alpha^O c_{ijk} + \beta^O h_{ijk} + x'_{ijk}\gamma^O + u_{ijk} \tag{3}$$

where the dependent variable is y_{ijk}^{O} 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, c denotes information access costs and h denotes communication 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 CHQ (e.g. how much investment could be made without CHQ 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 c). To be more explicit the four regressions we will estimate are:

Autonomy of the plant managers

$$y_{ijk}^{AP} = \alpha^{AP} ERP_{ijk} + \beta^{AP} NETWORK_{ijk} + x'_{ijk}\gamma^{AP} + u_{ijk}^{AP} \tag{4}$$

Autonomy of the worker

$$y_{ijk}^{AW} = \alpha^{AW}(CAD/CAM)_{ijk} + \beta_{ijk}^{AW} NETWORK + x'_{ijk}\gamma^{AW} + u_{ijk}^{AW} \tag{5}$$

Span of control of the plant manager

$$y_{ijk}^{SP} = \alpha^{SP}(CAD/CAM)_{ijk} + \beta_{ijk}^{SP} NETWORK + x'_{ijk}\gamma^{SP} + u_{ijk}^{SP} \tag{6}$$

Recall that Table 1 contains the main theoretical predictions of the model that we have sketched together with the technologies we are using. Column (1) corresponds to the three organizational outcomes we examine. Columns (2) through (4) refer to the effects of a fall in information costs and columns (5) through (7) to a fall in communication costs. Falls in information costs are associated with greater autonomy and larger spans of control (column (3)). 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.

5.2 Endogeneity

An obvious criticism of our modelling strategy is that there may be unobservables in equation (3) that are correlated with both the organizational outcomes and the ICT measures biasing our estimates of α^O and β^O. We have no plausible natural experiment to exploit so the evidence in this paper should be considered suggestive conditional correlations rather than causal.

Nevertheless, we do 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. We exploit these differential costs using OECD series on the prices of leased lines used for networks (call this price p_k^c). An obvious empirical problem is that these measured telecommunication price indices only vary across countries[16] 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 ($NETWORK_j$). We then estimate models of the form:

$$y_{ijk} = \lambda(p_k^c * NETWORK_j) + x'_{ijk}\mu + v_{ijk} \tag{7}$$

[16] 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).

Note that the controls (x'_{ijk}) include a full set of industry and country dummies, so we are essentially using $p^c_k * NETWORK_j$ as a direct proxy for h, so the prediction is that $\lambda > 0$: for the network-intensive industries we would expect to see more managerial autonomy in countries where communication prices are high (like Poland) than were they are low (like Sweden). More ambitiously we can potentially use $p^c_k * NETWORK_j$ as an instrumental variable for $NETWORK_{ijk}$. This is ambitious because we do not know exactly how intensively networks are used so $p^c_k * NETWORK_j$ may reflect this. We will try and assess the quality of this identification strategy (which parallels Rajan and Zingales, 1998) by using placebo experiments replacing p^c_k which other country-specific features such as GDP per head and education supply to make sure it is differential communication prices driving the results. We find that this is indeed the case. Unfortunately we do not have such a compelling identification strategy for information acquisition costs.

6 Empirical Results

6.1 Basic Results

Tables 3 through 5 present the main results, each table has a different dependent variable and corresponds to equations (4) to (6). Table 2 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[17], "noise" controls as discussed in the data section (there are 60 controls including analyst fixed effects) 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 CHQ) as the plant manager is allowed greater flexibility in making decisions over investment, hiring, marketing and product introduction. 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 manager. Column (2) includes skill as measured by proportion of employees with college degrees. The variable takes a positive and significant coefficient, indicating that more skilled workplaces tend to be more decentralized (consistently with Caroli and Van Reenen, 2001). This column also includes the PC intensity of establishment which enters

[17] Note that firms where the CEO was the same individual as the plant manager are dropped.

with a negative and insignificant sign. The ambiguity of the IT hardware variable should not be surprising as greater IT 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 10% level) which may reflect the fact that lower communication costs means that the CHQ start making more decisions than the plant manager as it is now easier to pass on solutions. This result is robust to including skills and PC 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. 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 follow exactly the same structure as 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 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 which we will discuss this more below). 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.

6.2 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 2000-2004[18]).

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[19]. 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 a reduction in worker autonomy of -0.005 standard deviations (equivalent to a 10.3% fall in the college share)[20]. 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.

Our takeaway from this is 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 and $NETWORK$ on all three organizational dimensions.

[18] 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.

[19] 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).

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

6.3 Extensions and Robustness

6.3.1 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 all positively correlated in the data, 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.

Nevertheless, a more direct way to confront the problem is to implement the idea discussed in the econometrics section of using the differential communication costs at the country level of "leased lines" (used for internal communication networks like intranets) as an exogenous factor shifting communication costs. We interact this country-specific variable (p_k^c) with the average adoption of networks in a three-digit industry across *all* countries included in our sample[21] (i.e. $p_k^c * NETWORK_j$). The idea behind this identification strategy is that for the same high network use industry, we are likely to have higher communication costs in Poland where telecommunications are still dominated by state-run incumbents compared to the Sweden where prices are lower due to a higher degree of liberalization. Note that all specifications absorb the linear effects with a full set of industry and country dummies[22].

The results for this experiment are presented in Table 6. The first column simply repeats the baseline specification from column (4) of Table 3 showing that network presence is associated with centralization[23]. The second column includes the key variable representing effective

[21] 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.

[22] Since the theoretical and empirical signs of the effects of $NETWORK$ on the span of control are ambiguous, we have not presented the results (they are all insignificant).

[23] Note that the sample is larger because we do not condition on ERP. This could also be endogenous and we have no valid instrument for it. Results are similar if we condition on ERP throughout this table (for example in column (2) the coefficient on the price term is 5.189 with a standard error of 2.221).

network prices. The positive coefficient on this variable is consistent with the idea that higher network costs reduces the use of networking technologies, and so enable plant managers to retain more autonomy. The magnitude of the coefficient suggests that for an industry where 10% of workers use networks doubling communication costs (e.g. moving from Sweden to Poland) decreases autonomy by 0.48 of a standard deviation. A concern is that the country-level network price variable simply proxies some other variable so we include country-level schooling and GDP per person in column (3). The network price variable remains positive and significant in sign.

We also examined an IV version of this identification strategy. Unfortunately, although prices were negatively correlated with Network usage the first stage was weak for $NETWORK$ (a |t| statistic of 1.5 on the instrument). Investigation revealed that this was because of low correlation for the smaller firms which may be because the OECD's communication price series includes discounts which are only available to larger users. When we dropped firms with under 200 employees the first stage was highly significant (a |t| statistic of 2.3). Running 2SLS on the larger firms generated a significantly negative marginal effect (-1.702 with a standard error of 0.95) suggesting downward bias on the OLS estimates[24].

Table 6 is consistent with the hypothesis that there is a causal effect of communication costs on organizational design.

6.3.2 "Cross" effects of technologies

We now consider some of the further "cross" effects of technologies by saturating the empirical models with all three types of technologies. Table 7 presents the full set of predictions from the theory analogously to Table 1. We present the most general specifications for each of the three organizational variables in Table 8. 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.

The first row includes CAD/CAM in the plant managers' autonomy equation which is insignificant in line with the theoretical prediction of a zero effect. The second row includes ERP in the workers' autonomy equation which is negative as theory predicts but insignificant. The last row 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 nega-

[24] We also examined a similar exercise for worker autonomy. The broad pattern of results was similar although no coefficient was significant. The problem is that $NETWORK$, although correctly signed is insignificant in the OLS worker autonomy equation.

tive. 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 organization.

6.3.3 Corporate Head Quarters' Span of Control

Table 7 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 Table 9.

The clear theoretical prediction from Table 1 is that ERP should be associated with a wider CHQ span because plant managers are able to make decisions more easily so the CHQ finds it easier to manage a larger number of them. This is supported by Table 8, 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 $NETWORK$[25]. The coefficient on $NETWORK$ is positive and significant (it has a theoretically ambiguous sign).

6.3.4 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 10 include a variable indicating the proportion of the plant manager's pay that was bonus (rather than flat salary)[26]. 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

[25] 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).

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

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 in the other columns and do not change the qualitative results.

Obviously this 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 a role for the cognitive theory we emphasis when looking at the impact of ICT.

6.3.5 Further Results

We have examined a large variety of robustness tests and some of these are presented in Table 11. 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 (2008) 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 now 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 belong (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)[27]. 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

[27] 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.

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. 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. The results again seem robust to these alternatives. The final column drop the size controls as they are endogenous in the theory with little impact on the results.

7 Conclusions

The empirical and theoretical literature that examines the economic effects of information and communication technologies (ICT) generally lumps together the information technology (IT) and communication technology (CT) into a single homogeneous mass. We argue that this is a serious error 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 decisions 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 headquarters 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). ERP provides a range of data on metrics like production, waste, energy use, sales, inventories and HR. Modern ERP systems increase dramatically the availability of information to managers, which should 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. The technology dataset is from a private sector data supplier (Harte-Hanks) that runs annual hardware and software surveys on about 1 million establishments across Europe and the US..

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 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 in networks are at a greater disadvantage in countries with high communication costs and use this to identify the effect of lower communication costs on decentralization.

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. 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 organization. Although we have plausible exogenous variation for network costs of communication, we do not have a similar quasi-experiment for information access. 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.

References

[1] Acemoglu Daron, Philippe Aghion, Claire Lelarge, John Van Reenen, and Fabrizio Zilibotti (2006) "Technology, Information and the Decentralization of the Firm" *Quarterly Journal of Economics,* 122 (4), 1759–1799

[2] Aghion, Philippe, and Tirole, Jean (1997), "Formal and Real Authority in Organizations," *Journal of Political Economy*, 105, 1-29.

[3] Alonso, Ricardo, Dessein, Wouter and Matouschek, Niko "When Does Coordination Require Centralization" (2008) *American Economic Review*, 98(1), pp. 145-179.

[4] Aubert, Patrick, Caroli, Eve, and Roger, Muriel (2006), "New Technologies, Workplace Organization and the Structure of the Workforce: Firm-Level Evidence," *Economic Journal*, 116, 73-93.

[5] Autor, David, Lavy, Frank and Murnane, Richard (2003) "The Skill Content of Recent Technological Change: An Empirical Exploration" *Quarterly Journal of Economics*, 118(4), 1279-1334

[6] Azmat, Ghazala, Manning, Alan, and Van Reenen, John (2008), "Privatization, Entry Regulation and the Decline of Labour's Share of GDP: A Cross-Country Analysis of the Network Industries", Centre for Economic Performance Discussion Paper No. 806

[7] Baker, George, Gibbons, Robert, and Murphy, Kevin (1999), "Informal Authority in Organizations," *Journal of Law, Economics, and Organization*, 15, 56-73.

[8] Baker, George, and Hubbard, Thomas (2003), "Make Versus Buy In Trucking: Asset Ownership, Job Design and Information", *American Economic Review*, 93, 551-72.

[9] Baker, George, and Hubbard, Thomas (2004), "Contractibility and Asset Ownership: On Board Computers and Governance in US Trucking," *Quarterly Journal of Economics*, 119, 1443-79.

[10] Baron, David, and Besanko, David (1992), "Information, Control, and Organizational Structure", *Journal of Economics and Management Strategy*, 1, 237-275.

[11] Bartel, Ann, Ichniowski, Casey and Kathryn Shaw (2007), "How Does Information Technology Really Affect Productivity? Plant-Level Comparisons of Product Innovation, Process Improvement and Worker Skills", *Quarterly Journal of Economics,* 122, No. 4, 1721-1758

[12] Beaudry, Paul, Doms, Mark and Lewis, Ethan (2006) "Endogenous Skill Bias in Technology Adoption: City-Level Evidence from the IT Revolution". NBER Working Paper, No 1251

[13] Black, Sandra, and Lynch, Lisa (2001), "How to Compete: The Impact of Workplace Practices and Information Technology on Productivity," *Review of Economics and Statistics*, 83, 434-445.

[14] Blanchard, Olivier (2004) "The Economic Future of Europe", *Journal of Economic Perspectives*, 18, 3-26.

[15] Bloom, Nick, Draca, Mirko and Van Reenen, John (2008) "Trade induced technical change: The impact of Chinese imports on technology and jobs" LSE/Stanford mimeo

[16] Bloom, Nick, Sadun, Raffaella and Van Reenen, John (2007), "Americans do I.T. Better: American multinationals and the productivity miracle" NBER Working Paper 13085

[17] Bloom, Nick, Sadun, Raffaella and Van Reenen, John (2008), "Measuring and Explaining Organization across firms and countries" LSE/Stanford mimeo

[18] Bolton, Patrick, and Dewatripont, Mathias (1994), "The Firm as a Communication Network," *Quarterly Journal of Economics*, 109, 809-839.

[19] Bresnahan, Timothy, Brynjolfsson, Erik, and Hitt, Lorin (2002), "Information Technology, Workplace Organization and the Demand for Skilled Labor: Firm-level Evidence," *Quarterly Journal of Economics*, 117, 339-376.

[20] Calvo, Guillermo, Wellisz, Stanislaw (1978), "Supervision, Loss of Control, and the Optimum Size of the Firm" *Journal of Political Economy,* 86, 943-952

[21] Caroli, Eve, and Van Reenen, John, (2001), "Skill Biased Organizational Change," *Quarterly Journal of Economics*, 116, 1448-1492.

[22] Colombo, Massimo, and Delmastro, Marco (2004), "Delegation of Authority in business organizations: An empirical test," *Journal of Industrial Economics*, 52, 53-80.

[23] Cremer, Jacques, Garicano, Luis and Prat, Andrea (2007), "Language and the Theory of the Firm" *Quarterly Journal of Economics,* 122(1): 373-407

[24] Davenport, Thomas H. , Harris, Jeanne G., Catrell, Susan (2002), "The Return of Enterprise Solutions: The Director's Cut." *Accenture Institure for High Performance Business Research Report,* October 2002.

[25] Dessein, Wouter (2002), "Authority and Communication in Organizations," *Review of Economic Studies*, 69, 811-838.

[26] Draca, Mirko, Sadun Raffaella and Van Reenen, John (2007), "Productivity and ICTs: a Review of the Evidence", in Robin Mansell, Chrisanthi Avgerou, Danny Quah and Roger Silverstone (eds.) *The Oxford Handbook of Information and Communication Technologies,* Oxford University Press.

[27] Garicano, Luis (2000), "Hierarchies and the Organization of Knowledge in Production," *Journal of Political Economy*, 108, 874-904.

[28] Garicano, Luis and Rossi-Hansberg, Estaban (2006), "Organization and Inequality in a Knowledge Economy" *Quarterly Journal of Economics*, 121(4), pp. 1383-435.

[29] Guadalupe, Maria and Wulf, Julie (2008) "The Flattening Firm and Product Market Competition: The Effect of Trade Liberalization", Harvard Business School Strategy Unit Working Paper No 09-067

[30] Hart, Oliver, and Moore, John (2005), "On the Design of Hierarchies: Coordination versus Specialization," *Journal of Political Economy*, 113, 675-702.

[31] Harris,Jeanne G. and Davenport, Thomas H (2006),"New Growth from Enterprise Systems: Achieving High Performance through Distinctive Capabilities", *Accenture Institute for High Performance Business Report.*

[32] Kretschmer, Tobias and Mahr, Ferdinand (2009) "Complementaries between technologies: Survey Evidence", University of Munich mimeo

[33] Manski, Charles (2004), "Measuring expectations", *Econometrica*, LXXII (5), 1329-1376.

[34] Lemieux, Thomas, MacCleod, Bentley and Parent, Daniel (2007) "Performance Pay and Wage Inequality" NBER Working Paper 13128, forthcoming *Quarterly Journal of Economics*

[35] Machin, Stephen and Van Reenen, John (2008) "Changes in Wage Inequality" in Weinberg, Bruce and Taber, Christopher (eds) *New Palgrave Dictionary of Economics,* London: Palgrave

[36] Melumad, Nahum, Mookherjee, Dilip, and Reichelstein, Stefan (1995), "Hierarchical Decentralization of Incentive Contracts," *Rand Journal of Economics*, 26, 654-672.

[37] Milgrom, Paul, and Roberts, John (1990), "The Economics of Modern Manufacturing: Technology, Strategy and Organization," *American Economic Review*, 80, 511-528.

[38] Prendergast, Canice (2002) "The Tenuous Trade-off between Risk and Incentives" *Journal of Political Economy*, 110 (5), 1071-1102

[39] Radner, Roy (1993), "The Organization of Decentralized Information Processing," *Econometrica*, 61, 1109-1146.

[40] Rajan, Raghuram G and Zingales, Luigi (1998) "Financial Dependence and Growth" *American Economic Review*, 88(3), 559-86

[41] Rajan, Raghuram, and Wulf, Julie (2006), "The Flattening Firm: Evidence from Panel Data on the Changing Nature of Corporate Hierarchies," *Review of Economics and Statistics*, 88 (4), 759-773

[42] Shepard, Jim and Eric Klein (2006), *Enterprise Resource Planning Spending Report, 2006-2007.* AMR Research.

[43] Stephenson, Betsy (2006) "The Impact of the Internet on worker flows", Wharton Business School mimeo

[44] *Telecommunication Handbook*, (2007), OECD: Paris

[45] World Development Indicators (2006) World Bank: Washington DC.

APPENDICES

A Appendix A: Proofs

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

$$\begin{aligned} foc_{z_p} &: \quad -c_p + \left((c_m + c_m x_m + w_m) + (c_c + w_c)h(1-G(x_m))\right) hf(z_p) = 0 \\ foc_{x_m} &: \quad [-c_m + (c_c + w_c)hg(x_m))]h(1-F(z_p)) = 0 \end{aligned}$$

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

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

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

$$H = \begin{pmatrix} \left((c_m + c_m x_m + w_m) + (c_c + w_c)h(1-G(x_m)\right) hf'(z_p) & 0 \\ 0 & h(c_c + w_c)g'(x_m) \end{pmatrix}$$

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$= (foc_{z_p} foc_{x_m})$:

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

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:

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

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: $s_m = N/n_m = 1/\left((1-F(z_p)h\right)$,

$$sign\begin{pmatrix} \frac{\partial s_m}{\partial c_p} \\ \frac{\partial s_c}{\partial c_p} \end{pmatrix} = \begin{pmatrix} <0 \\ 0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial s_m}{\partial c_m} \\ \frac{\partial s_c}{\partial c_m} \end{pmatrix} = \begin{pmatrix} >0 \\ <0 \end{pmatrix}; sign\begin{pmatrix} \frac{\partial s_m}{\partial h} \\ \frac{\partial s_c}{\partial h} \end{pmatrix} = \begin{pmatrix} \lesseqgtr 0 \\ \lesseqgtr 0 \end{pmatrix}.$$

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 c_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 $c_c = c_m$. The first foc becomes $foc_{z_p} : -c_p + ((c_m + c_m x_m + w_m) + (c_m + w_c)h(1 - G(x_m))\, hf(z_p)$, foc_{x_m} changes to: $-c_m + (c_m + w_c)hg(x_m))$, and

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

so that sign$\begin{pmatrix} \frac{\partial z_p}{\partial c_m} \\ \frac{\partial x_m}{\partial c_m} \end{pmatrix} = \begin{pmatrix} > 0 \\ < 0 \end{pmatrix}$ 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 (2008) 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"

Figures 5 and 6 show the distribution of answers to these questions. It is clear from these figures 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 responses within respondent, i.e. looking at the relative responses for the same respondent 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 c_m downwards to a similar extent as c_c which is again, what we assumed for our interpretation of the empirical results[28].See Kretschmer and Mahr (2009) for full details on the underlying survey.

C Appendix C: Main Dataset

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, Greece, 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 5000 employees on average over the most recent three years of data (typically 2002 to 2004)[29].

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[30]. 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 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[31]. As a robustness test we also drop

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

[29] 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).

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

[31] 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

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 global company 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 roughly 160,000 establishments across 20 European countries as well as the US. The US branch has the longest history with the company beginning its data collection activities in the mid 1980s. The papers by Bresnahan et al (2002) and Brynjolfsson and Hitt (2003) use a sub-set of the US Harte-Hanks data matched to large publicly listed firms in Compustat. In Europe, the company began surveying the major Western European countries (UK, France, Germany, Italy, Spain) in the early 1990s, and by the late 1990s had expanded to cover the rest of Western Europe.

Harte Hanks surveys establishments (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 establishment level. Areas covered by the survey include PCs, many types of software, servers, storage and IT staff (including development staff such as programmers). We focus on using PC per worker as our key measure of IT hardware intensity because this is available for all the establishments and is measured in a comparable way across time and countries. This PC per worker measure of IT has also been used by other papers in the micro-literature on technological change and is highly correlated with other measures of IT use like the firm's total IT capital stock (see, for example, Doms et al, 2006).

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

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.

future sales[32]. Because of this HH run extensive internal random quality checks on its own data, enabling them to ensure high levels of data accuracy.

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 establishment employment - so the data contains establishments with less than 100 employees in firms with multiple establishments. Furthermore, HH only drops establishments 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.

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 and the U.K.) and on Icarus for the US

D 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).

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

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

		Reduction in Communication costs *(h)*			Reduction in Information costs *(c)*		
(1)		**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
		Technology Indicator	**Theoretical Prediction**	**Empirical Finding**	**Technology Indicator**	**Theoretical Prediction**	**Empirical Finding**
Plant Manager Autonomy	*(Table 3)*	*NETWORK (h)*	-	-	*ERP* (c_m)	+	+
Worker Autonomy	*(Table 4)*	*NETWORK (h)*	-	-	*CAD/CAM* (c_p)	+	+
Plant Manager Span of Control	*(Table 5)*	*NETWORK (h)*	?	+	*CAD/CAM* (c_p)	+	+

Notes: This table presents the theoretical predictions and the empirical findings. Column (1) has the organizational outcomes: autonomy (for plant manager and worker) and span of control (for plant manager and CEO). *NETWORK* denotes the presence of a network (leased line/frame relay), *ERP* denotes Enterprise Resource Planning and *CAD/CAM* denotes Computer Assisted Design/Computer Assisted Manufacturing. A "+" denotes an increase, a "-'' a decrease a "0" denotes no effect and "?'' denotes an ambiguous sign. All results except for Worker Autonomy column (4) and Plant Manager Span of Control column (4) 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
PC 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)
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(PC/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 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 - WORKER AUTONOMY

	(1)	(2)	(3)	(4)	(5)	(6)
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(PC/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 firms	687	687	687	687	687	687

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 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)
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(PC/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 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 (USING EFFECTIVE NETWORK PRICES AS EXOGENOUS SHIFTER OF NETWORK USAGE)

	(1)	(2)	(3)
Regression	**Basic**	**Reduced Form**	**Reduced Form**
Estimation Method	**OLS**	**OLS**	**OLS**
Dependent Variable	**Plant Manager Autonomy**	**Plant Manager Autonomy**	**Plant Manager Autonomy**
Sample	**All**	**All**	**All**
Firm-level NETWORK	-0.132*		
	(0.068)		
(Industry-level NETWORK %) *ln(NETWORK Price)		4.791**	5.802**
		(2.189)	(2.766)
(Industry-level NETWORK %)* ln(Average Years of Schooling)			1.443
			(5.024)
(Industry-level NETWORK %)*ln(GDP Per Capita)			1.541
			(2.546)
Number of Firms	1,020	1,020	1,020

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 country by three digit industry pair in all columns. 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 noise controls, firm controls and industry dummies as in previous tables. “Firm-level NETWORK” represents access to an internal network (leased lines or frame relays). “Industry-level NETWORK” represents the fraction of workers with access to an internal network (leased lines or frame relays) in the three digit industry across all countries (see text). “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). The variables “Average Years of Schooling” and “GDP Per Capita PPP” are taken from the World Development Indicators (2006).

TABLE 7 – EXTENDED THEORY PREDICTIONS

(1)	*(2)*	*(3)*	*(4)*	*(5)*
Type of technological change		*Reduction in communication ("helping") costs*	*Reduction in information acquisition costs for production decisions*	*Reduction in information acquisition costs for non-production decisions*
		h	c_p	c_m
		NETWORK	**CAD/CAM**	**ERP**
Organizational Outcome				
Plant Manager Autonomy	x_m	-	0	+
Worker Autonomy	z_p	-	+	-
Plant Manager Span of Control	s_m	?	+	-
CEO Span of Control	s_c	?	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. An "insig." Denotes that a variable was insignificant at the 5% level (all other variables were significant at this level).

TABLE 8 – CROSS EFFECTS OF TECHNOLOGIES

Dependent Variable	**NETWORK**	**CAD/CAM**	**ERP**	**Firms**
Plant Manager Autonomy	-0.111**	0.091	0.116**	859
	(0.053)	(0.223)	(0.054)	
Workers' Autonomy	-0.228	0.532*	-0.290	687
	(0.180)	(0.275)	(0.177)	
	[-0.023]	[0.053]	[-0.029]	
Ln(PM Span)	0.020	0.156**	0.053	948
	(0.054)	(0.076)	(0.043)	

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 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 9 – CEO SPAN OF CONTROL

	(1)	(2)	(3)
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(PC/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 Firms	1,069	1,069	1,069

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 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 10 CONTROLLING FOR INCENTIVES

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 For typical manager	0.478**	-0.260	0.086			
	(0.235)	(0.727)	(0.141)			
		[-0.026]				
% Salary Increase on Promotion For a typical manager				-0.025	0.479	0.168
				(0.220)	(0.597)	(0.131)
					[0.045]	
Number of Firms	948	687	859	948	687	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 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.

TABLE 11 - 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 as an additional control	(7) Alternative dependent variable	(8) Drop size controls
				Panel A: Plant Manager Autonomy				
ERP	0.116**	0.096*	0.112**	0.114**	0.118**	0.119**	0.133**	0.125**
	(0.054)	(0.052)	(0.054)	(0.053)	(0.053)	(0.054)	(0.059)	(0.054)
NETWORK	-0.110**	-0.127**	-0.098*	-0.134**	-0.125**	-0.112**	-0.099*	-0.115**
	(0.053)	(0.052)	(0.053)	(0.063)	(0.051)	(0.053)	(0.056)	(0.054)
Firms	948	948	948	948	948	948	948	948
				Panel B: Workers' Autonomy				
CAD/CAM	0.535*	0.650**	0.566**	0.641**	0.458	0.492*	0.863**	0.534*
	(0.274)	(0.284)	(0.285)	(0.268)	(0.280)	(0.275)	(0.342)	(0.277)
	[0.053]	[0.049]	[0.054]	[0.061]	[0.065]	[0.049]	[0.242]	[0.054]
NETWORK	-0.226	-0.402*	-0.236	-0.659***	-0.230	-0.263	-0.090	-0.227
	(0.180)	(0.211)	(0.190)	(0.249)	(0.174)	(0.184)	(0.217)	(0.181)
	[-0.023]	[-0.03]	[-0.022]	[-0.063]	[-0.021]	[-0.026]	[-0.017]	[-0.023]
Firms	687	687	687	687	687	687	687	687
				Panel C: Plant Manager Span of Control				
CAD/CAM	0.155**	0.208***	0.157**	0.153**	0.156**	0.156**		0.167**
	(0.075)	(0.075)	(0.075)	(0.075)	(0.074)	(0.074)		(0.074)
NETWORK	0.035	0.045	0.030	0.069	0.048	0.035		0.052
	(0.041)	(0.042)	(0.041)	(0.058)	(0.040)	(0.041)		(0.042)
Firms	859	859	859	859	859	859		859

Notes: * = significant at the 10% level, **= significant at the 5% level, ***=significant at the 1% level. Panel A and C estimated by OLS. Panel B is estimated by probit ML with standard errors in parentheses and marginal effects in square brackets. Standard errors are clustered by firm in all columns and panels. The 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" 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. 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 dummy equal to unity if the firm is publicly listed 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 controls. 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.

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

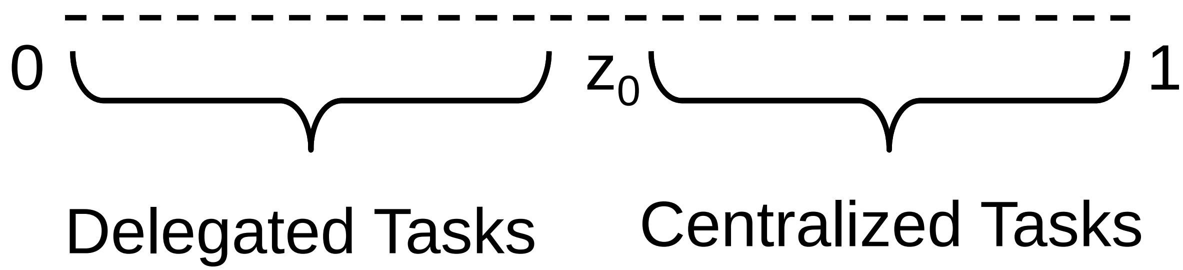
Question D7: "Who decides the pace of work on the shopfloor"

	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

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

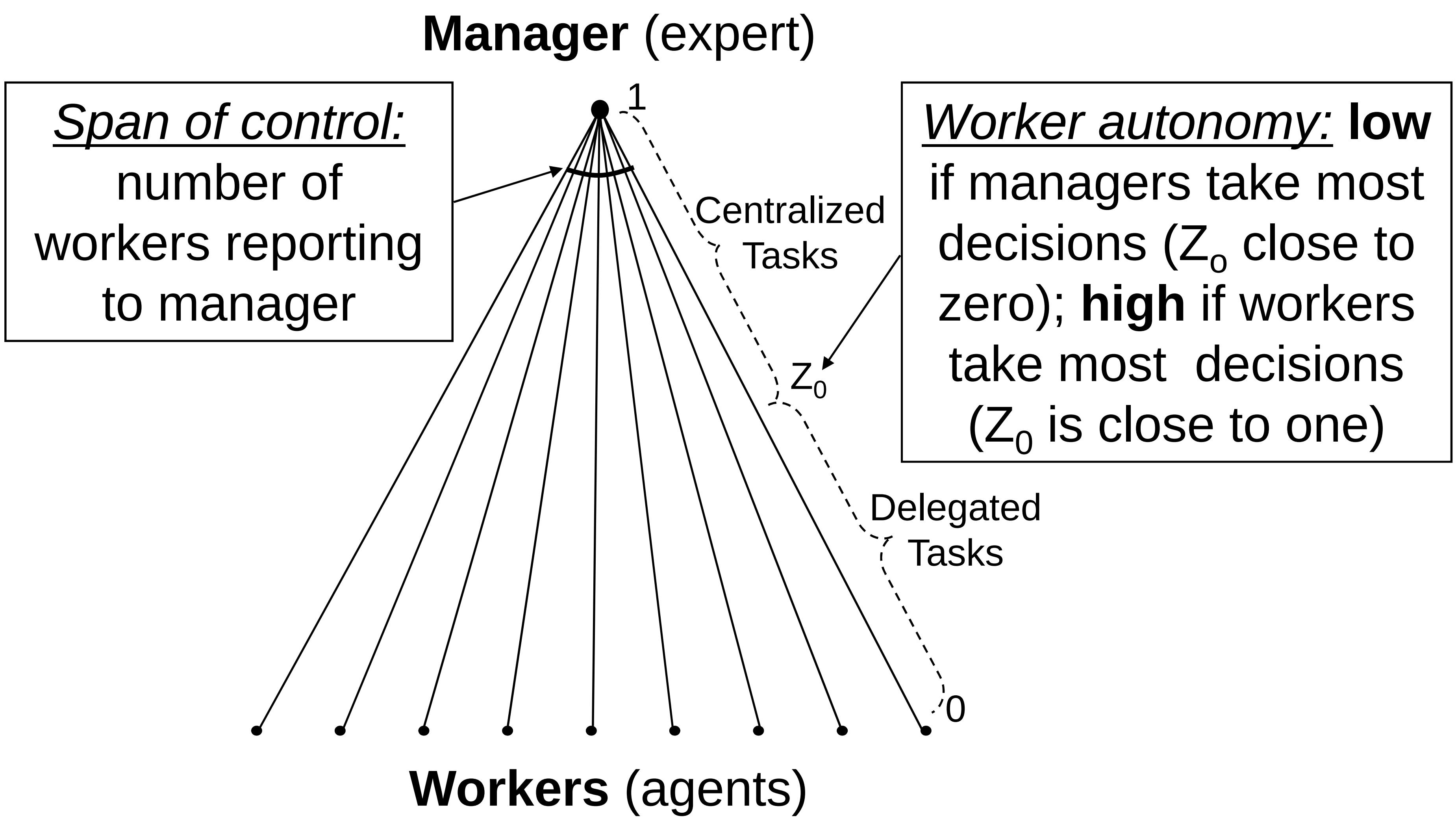
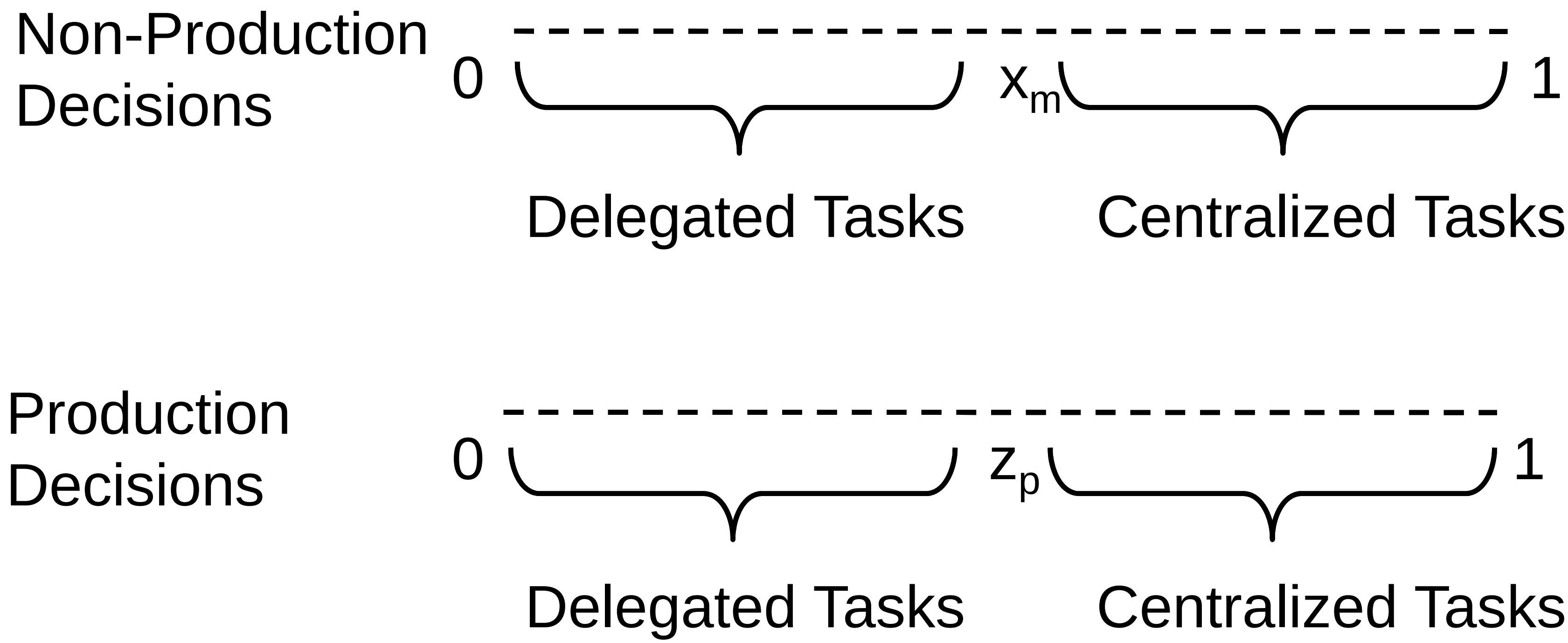


Figure 3: Delegation of tasks in the extended model



Notes: This generalizes Figure 1 where we allow for non-production decisions and production decisions. Non-production decisions below *xm* are performed by plant managers, the rest by Central Head Quarters. Production decisions below *z0* are performed by production workers, the rest by plant managers

Figure 4: Information and communication

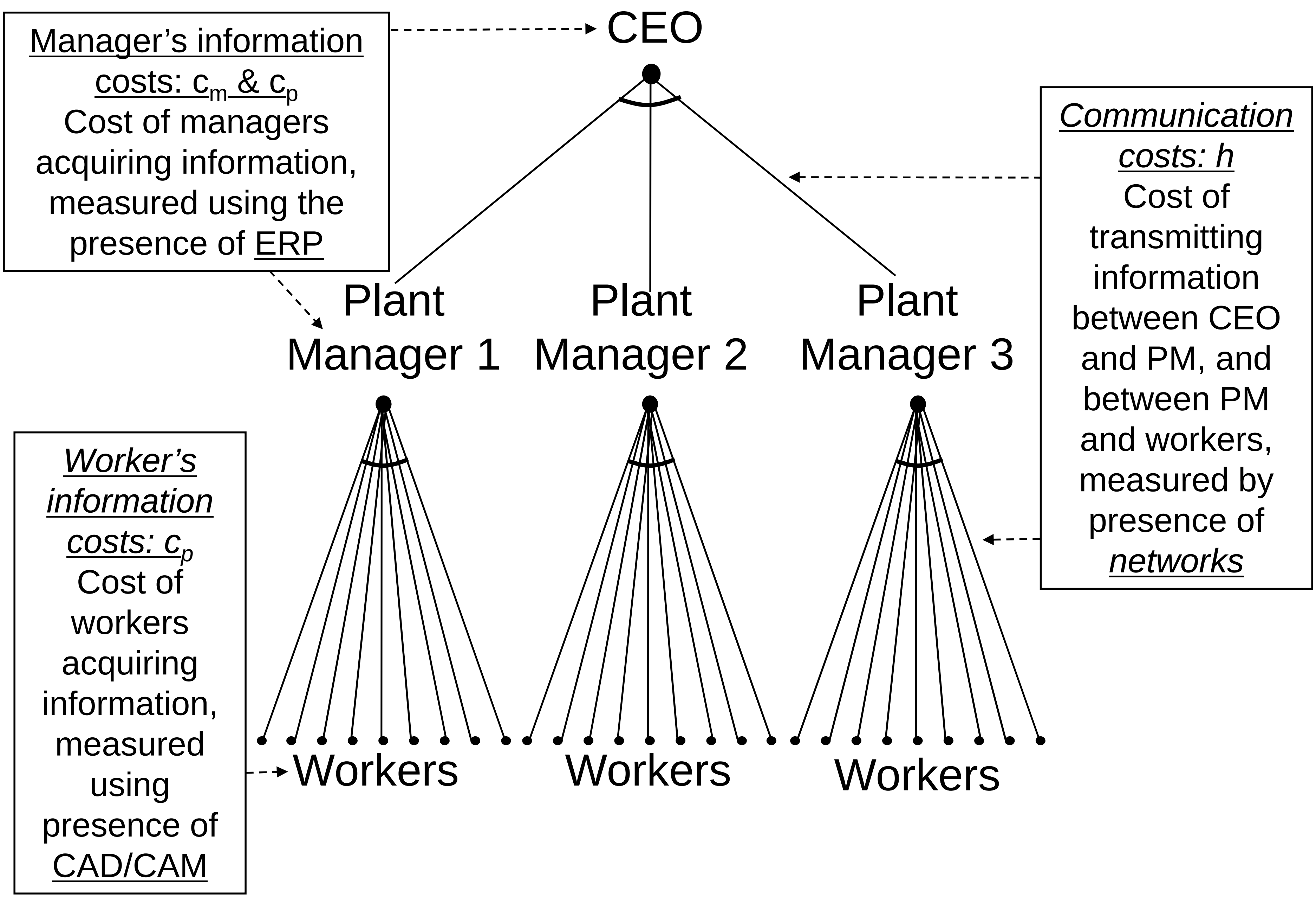
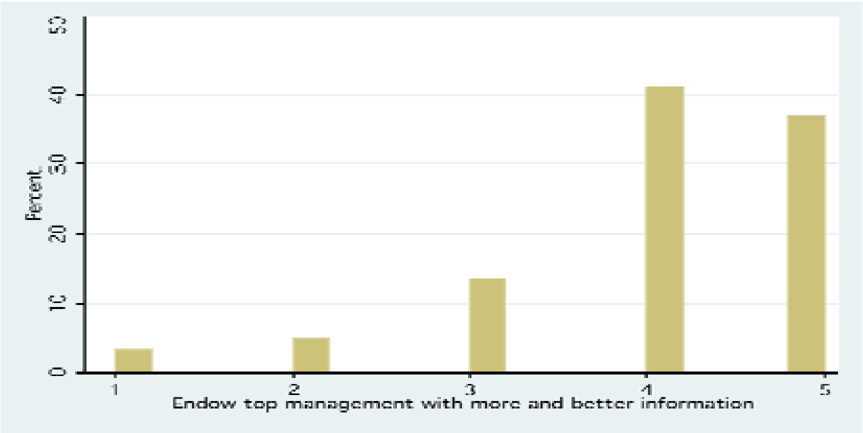
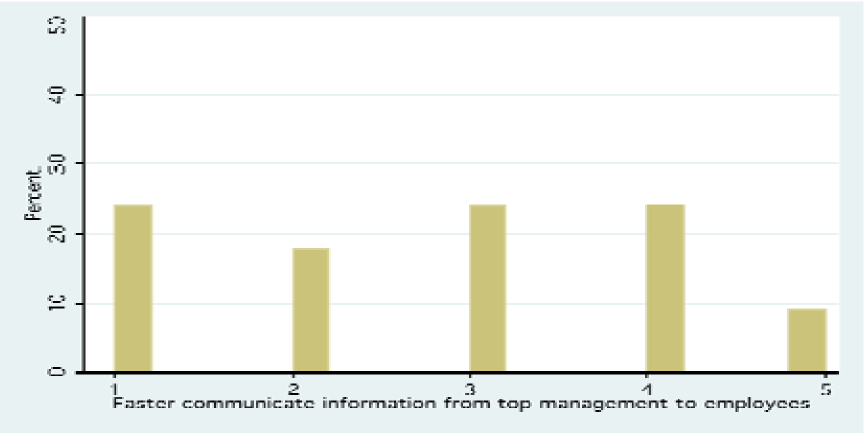


Figure 5: Enterprise Resource Planning (ERP) use

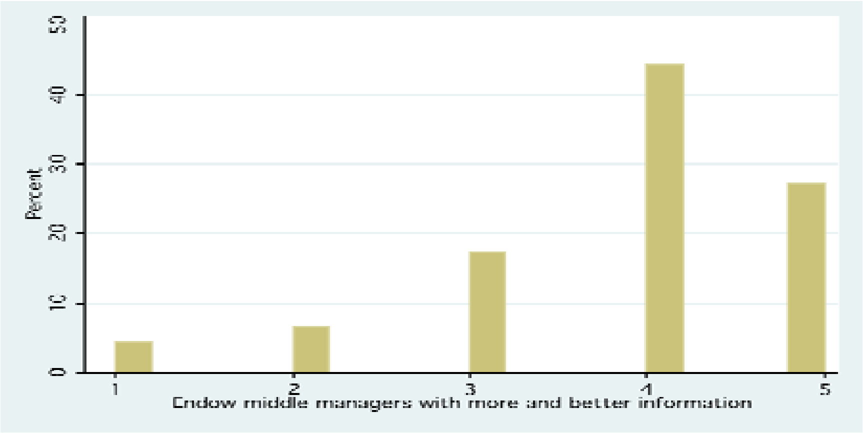
<u>**Q1:**</u> *"Our ERP System is used to endow **top management** with more & better **information**"*



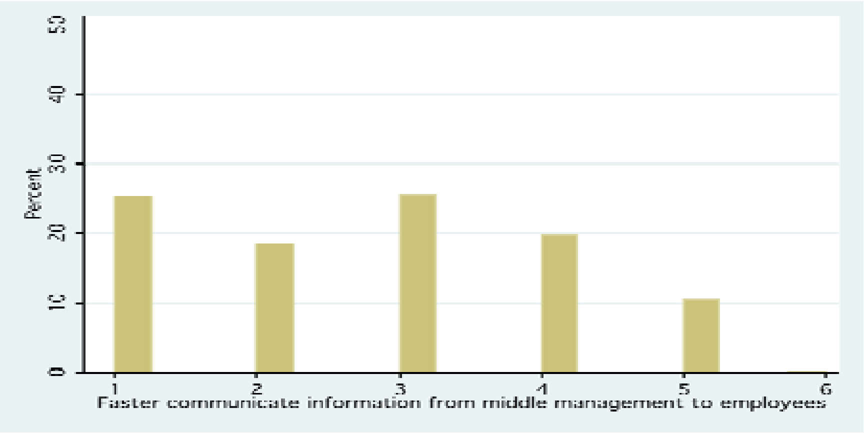
<u>**Q2:**</u> *"Our ERP System is used to faster **communicate** information and directives from **top management** to employees"*



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



<u>**Q4:**</u> *"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.