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► To cite this version:

Hans Peter Grüner. Information Technology, Efficient Restructuring and the Productivity Puzzle. Journal of Economic Behavior and Organization, 2009, 72 (3), pp.916. 10.1016/j.jebo.2009.09.003 . hal-00748068

HAL Id: hal-00748068

<https://hal.science/hal-00748068>

Submitted on 4 Nov 2012

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Accepted Manuscript

Title: Information Technology, Efficient Restructuring and the Productivity Puzzle

Author: Hans Peter Grüner

PII: S0167-2681(09)00218-2
DOI: doi:10.1016/j.jebo.2009.09.003
Reference: JEBO 2449

To appear in: *Journal of Economic Behavior & Organization*

Received date: 27-1-2009
Revised date: 6-9-2009
Accepted date: 6-9-2009

Please cite this article as: Grüner, H.P., Information Technology, Efficient Restructuring and the Productivity Puzzle, *Journal of Economic Behavior and Organization* (2008), doi:10.1016/j.jebo.2009.09.003

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Information Technology, Efficient Restructuring and the Productivity Puzzle*

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January 2009

*I thank an anonymous referee, an associate editor, Peter Funk, Eckhard Janeba, Micael Castanheira, Axel Ockenfels, Elisabeth Schulte and seminar participants at Cologne, Mannheim, Warwick and Gerzensee for their helpful comments and suggestions.

Information Technology, Efficient Restructuring and the Productivity Puzzle

Abstract Labor productivity in the US has recently grown more strongly than in most European countries. It is often argued that the American productivity increase is due to the widespread introduction of new information and communication technologies (ICT). But why have the same technologies not similarly increased Europe's labour productivity? This paper provides a theoretical explanation for this productivity puzzle based on an extension of Radner's (1992) model of hierarchical information aggregation. The introduction of new ICTs enables organizations to process any given amount of information with a shorter delay. This enables organizations to restructure and solve incentive problems without risking to produce with excessive delay. Even a marginal improvement in the ICT can yield significant increases in labor productivity if - and only if - the organization is drastically restructured. Restructuring yields hierarchies with fewer layers and fewer managers, all working under incentive pay and providing first best effort. However, managers need not participate in the gains associated with the restructuring of their business firms.

Keywords: Information processing, hierarchies, restructuring, labor productivity, ICT.

JEL: D23, D70, D83, L22, P51.

1 Introduction

Over the last two decades, US labor productivity has grown more strongly than in most European countries. Many observers argue that the American productivity increase is due to the introduction of new information and communication technologies¹. This includes the widespread use of new communication devices such as the internet, e-mail, mobile phones, and mobile computers with wireless internet access as well as new more comfortable software products for word-processing and statistical applications. However, these innovations were also used immediately by many European firms (Jorgensen and Vu, 2007). If they are the key explanation for the impressive American productivity increase, then why haven't they increased European labour productivity to a comparable extent?

The present paper provides a theoretical explanation for this productivity puzzle. It analyzes the way in which innovations in information and communication technologies affect the optimal design of organizations. The explanation for the puzzle put forward here is the following. The introduction of new IC-technologies enables organizations to process any given amount of information with a shorter delay. This means that organizations can reduce the division of labor and solve incentive problems without risking to produce with excessive delay. Restructuring generates a higher surplus when the number of employees involved in a particular process is reduced. It enables the principal to better address free rider problems in team production processes. Under a proper incentive contract, the reduction of the number of employees increases equilibrium effort. Therefore, an improved IC-technology enables restructured organization to produce more efficiently for a given delay.²

I show that even a marginal improvement of the IC-technology can yield significant in-

¹Oliner and Sichel (2000, p.3) estimate that "the use of information technology and the production of computers accounted for about two-thirds of the 1 percentage point step-up in productivity growth between the first and second halves of the decade." According to Gordon (2004) the US-EU productivity gap has been largest in the IT- intensive sectors.

²A similar effect of technological innovations has most likely affected the organization of upper class households over the last century. According to Davis (2008), "servants were imperative to the functioning of middle and upper class homes in Victorian England. Without the veritable army of servants for the upper and upper-middle classes, women would not be able to live the leisured lives they had grown accustomed, and would certainly not have the time to flaunt their status with neighbor-calling and the numerous balls and social activities", but even "most lower-middle and middle-middle classes employed at least one servant, as assistance was almost a necessity in maintaining the home" (see also Roberts, 2003). Technical progress made it possible to perform many household tasks in a much shorter time span. As a consequence, the former principals now perform a much more heterogeneous set of tasks.

creases in labour productivity if the organization is restructured appropriately. Moreover, marginal changes in ICT productivity may result in a significant restructuring of organizations. Several hierarchy levels may disappear and the optimal organization employs fewer managers for each individual processing task. Note that this does not necessarily imply a reduction of the overall size of business firms. It rather means that the number of managers who work on particular projects within firms is reduced significantly.³

An improved IC technology without an appropriate restructuring instead yields only marginal productivity gains. Hence, there is a strong complementarity between IC technology improvements and a lean organizational design. If the organization avoids restructuring then the productivity increase remains marginal. A straightforward explanation for the productivity puzzle is that European companies have been more reluctant to restructure their production process in an appropriate manner. If complementarities are not made use of, then the productivity effect of ICT improvements cannot fully be exploited.

In the model a principal hires a number of agents called managers who work on a given number of information items. Each agent has to provide effort in order to properly understand the information that he is supposed to handle. Agents have to process all items in order to realize a high output level. Unobservable additional effort on objects increases the likelihood of the good outcome. First-best effort cannot be implemented because all agents are wealth-constrained. The overall success probability of the organization is increasing in the aggregate amount of effort provided by all employees.

In the first example of section 4 I impose a uniform sharing rule for the management team. All managers get the same share of the project's output. Under this rule most of our results can be derived quite easily. Generally, it may be optimal to provide only a subset of managers with monetary incentives and to distribute the surplus unevenly. In section 6 I discuss the general case. Without any restrictions on the sharing rule it is optimal to provide only a fraction of the employees with incentives for extra effort. The restructuring process that follows an ICT productivity increase may then lead to a situation in which all remaining employees work under monetary incentives.

Section 7 addresses the question of why workers or managers may be willing to forgo the efficiency gains that are associated with the restructuring of their firms. Can't they be compensated if the firm produces more efficiently? And won't new firms hire those workers who have been dismissed by others? We address these questions in a macroeconomic extension of the basic model in which capital (or the number of available projects) is

³See Earle, Pagano, and Lesi (2006) for an empirical analysis of the relationship between firm size and technology adoption.

fixed. In such a setup optimal restructuring can lead to an excess supply of workers which reduces labor rents. Therefore, countries in which labor is politically powerful end up with inefficient production processes that hire too many workers and artificially generate labor rents.

2 Related literature

The model in this paper analyzes the way in which innovations in information and communication technologies affect the design of organizations. The paper is related to two recent strands of the literature on organizational design. The first one imports insights from computer science into economic theory. This literature introduces a delay of information processing into economic models. It started with Radner (1992, 1993) and Radner and van Zandt (1992). The resulting optimal "reduced tree" structure is designed for one-shot problems in which there is only one set of data to be processed, or the processing of the data is finished before another calculation task occurs. I restrict attention to this case in most of the paper. Van Zandt (1997, 1998) and Meagher, Orbay and van Zandt (2001) study the case when new data comes in before the processing of the old set is finished. Orbay (2002) adds the frequency with which new data arrives as a new dimension to the analysis of efficient hierarchies. A similar problem is addressed in the appendix of this paper.

The paper is also closely related to the recent work by Garicano (2000) and Garicano and Rossi-Hansberg (2004,6) on the microeconomic and distributional consequences of IT innovations. These papers address related questions in a different framework. Garicano introduces a model of hierarchical information aggregation. In this model agents may either specialize in a problem solving or in providing advice to other problem solvers. Two variables measure the quality of information technology: the cost of acquiring knowledge and communication costs. While a reduction of the cost of knowledge unambiguously reduces the number of hierarchy layers, communication costs have an ambiguous effect because lower communication costs encourage firms to choose more division of labor. In the present paper a hierarchy has the task of aggregating decentralized information. The paper focuses on the trade off between faster information aggregation and an incentive effect of the division of labor. Lower communication costs lower the benefits for the division of labor and organizations can provide better incentives. The size of a hierarchy always declines with information transmission costs.⁴

⁴Note that my notion of hierarchy layers is different from Garicano's. In his paper the number of

Garicano and Rossi Hansberg (2004,6) study a macroeconomic extension of Garicano's model that uses a matching equilibrium similar to the ones in Legros and Newman (2002). They identify a number of interesting effects of IT innovations on the equilibrium income distribution within skill groups. The present paper also studies a macroeconomic matching equilibrium. However, it concentrates on the distributional conflict between scarce capital and management or labor.

Meagher, Orbay and Van Zandt (2003) study the impact of information technology on the organization of a business enterprise which collects data on changing market conditions. Collecting more data is useful per se but the delay of the analysis reduces the usefulness of the outcome when the environment changes over time.⁵ Meagher (2003) studies the impact of ICT innovations on firms' internal organization and incentive schemes in a framework with a managerial production function. He finds that a linear increase in productivity (which he interprets as an IT improvement) increases the size and scope of firms.

In Radner's model – and in most of the information processing literature which followed – individuals are thought of as machines, perfectly doing what they are programmed to do. The joint analysis of speed and quality of hierarchical decision processes has previously been studied in Grüner and Schulte (2004), Jehiel (1999) and in Schulte and Grüner (2007). Jehiel considers the case where some signals get lost in the hierarchy with an exogenous probability, depending on the size of the groups of which the hierarchy consists. Schulte and Grüner study the role of the hierarchy design when individuals make mistakes with an exogenously given probability. In the present paper, the quality of collected information is endogenously determined by the actions of self-interested agents. The result that the reduced tree provides a (weakly) better decision quality than other organizations is the same. Grüner and Schulte (2004) have provided a first game theoretic analysis of the interaction of agents with incentive problems in such an organization.

hierarchy layers is the number of sets of agents with different knowledge. Not all items need to go through the entire hierarchy because information is not aggregated. In the present model the size of the hierarchy determines the maximum number of operations an initial item needs to go through until it reaches the top player.

⁵Prat (1997) studies hierarchies in which some managers are able to work faster than others, and the wage a manager is paid is a function of his ability. It turns out that with these modifications – except for the one made by Prat (1997) – the reduced tree is still (close to) efficient. Bolton and Dewatripont (1994) allow for specialization, which reduces the time an agent needs to understand information he handles frequently. In their model, the trade-off between specialization and communication costs determines the extent and the form of decentralization.

The present paper contributes an analysis of the relationship between technology and organization to this literature.

The paper is also related to the extensive game theoretic literature that studies incentives in hierarchies, such as Aghion and Tirole (1997), Mookherjee and Reichelstein (1997), and Melhumad, Mookherjee and Reichelstein (1995). These papers consider problems in which certain tasks as well as authority have to be delegated (and sub-delegated) to (and by) agents whose interests diverge from that of the principal. Delegation involves a loss of control for the principal, but strengthens the incentives for the agent. In the present model, all agents only care about the amount of effort they provide, not about the decision per se.⁶

A related moral-hazard-in-team problem is studied in Dewatripont and Tirole (2004). They consider a sender-receiver game, where the sender has payoff-relevant information for the receiver, and must invest unobservable effort for the receiver to understand the information. In my model, communication is costless for the sender, but he has to provide effort to acquire the information in the first place.⁷

Recently, Acemoglu, Aghion, Lelarge, Van Reenen, and Zilibotti (2007) analyzed the relationship between the diffusion of new technologies and the decentralization decisions of firms. Firms closer to the technological frontier and firms in more heterogeneous environments are more likely to choose decentralization.

An important early contribution that stresses complementarities in production is Milgrom and Roberts (1990). The paper explores the effect of introducing CAD/CAM software in manufacturing plants and describe the chain reaction of business process redesign that occurs as a result. Milgrom and Roberts (1995) further explores their theory and includes a case study of Lincoln Electric.

Finally, there are several recent papers that also address the productivity puzzle such as Gordon (2004), Prescott (2006) and Klump et al. (2006). Most closely related is the paper by Gordon (2004) who argues that poor institutions prevented the realization of IT

⁶Another related paper is Winter (2004), who studies incentive provision in a hierarchy via a transfer scheme. In his paper, the n tasks are assigned to n agents right from the beginning. He does not allow for the possibility to assign tasks differently, nor that one agent performs all of them. Unlike Winter, I am interested in the effect of task assignment on effort provision.

⁷Other papers derive decentralized (hierarchical) organizations from technology. Crémer (1980) considers a problem of resource allocation under constraints on managerial time and finds that hierarchical organizations increase the amount of information that can be applied to a particular decision. Rosen (1982) has a paper in which a hierarchical structure emerges due to the need to supervise production (and supervision).

induced productivity gains in Europe. In particular he lists policies that promote high-density metropolitan areas, a lack of competition, and a poor public system of research financing. Others focus on the role of labor supply versus labor productivity measured as output per hours worked. Interestingly, both the average number of hours worked and productivity per worker is higher in the US than in Europe. As will be argued below, both observations are compatible with the present theory. According to Prescott (2006) Americans work 50 percent more than do the Germans, French, and Italians. He argues that taxes account for the differences in labor supply across time and across countries, in particular, the effective marginal tax rate on labor income.

3 The model

3.1 The information aggregation task

Consider the following information aggregation task. A principal hires a team of m agents who have to work on n information-items. Agents work in a programmed hierarchy. Each agent reports the result of his operations to a single superior. There is a top agent who makes the final decision. Each item is assigned to exactly one agent. The programme determines at what point of time an agent is supposed to report to his superior (see Radner 1993 for a detailed description of the concept of a programmed network). Each agent can privately choose to provide normal or extra effort on an item. The cost of normal effort is normalized to zero. Providing extra effort is costly, the cost per item is measured in monetary units and denoted by $c > 0$. I call a the number of items on which agents have provided extra effort, and $b = n - a$ the number of items that have been read without extra effort. Whether or not an agent has provided normal effort is observable and verifiable. The decision on extra effort is not observable. For simplicity, I assume that any report about the aggregate of information items from a lower hierarchy level can fully be understood by the superior without extra effort.

Agents communicate effectively in the sense that all the available information on initial items or aggregates thereof is transmitted accurately to the top agent in the hierarchy. However, no agent is able to derive the amount of effort that has been provided by a subordinate from his message.

The hierarchy's output x can take two values, 1 or 0. The probability of success π directly depends on the amount of effort that has been provided in the hierarchy. The chance of realizing a high output is linear in a and b . Moreover, it decreases in delay d .

$$\pi = \begin{cases} ap + bq - f(d) & \text{if } a + b = n, \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

with

$$f(0) = 0, \quad f'(0) = 0, \quad f \text{ non-decreasing,} \quad (2)$$

and

$$1/n \geq p > q > 0. \quad (3)$$

Providing effort is efficient, i.e. $p - q > c$. If one item is not read then the probability of success is zero. If all items are read but no agent provides extra effort then the probability of success is $nq > 0$. Thus, when all items are read, we may write expected profits as:

$$\pi = nq + a(p - q) - f(d). \quad (4)$$

Both a shorter delay and more effort provision increase expected profits. Figure 1 displays the corresponding iso-probability-of-success curves that emerge from a convex cost of delay function. The vertical axis measures the effort-related component of the success probability.

In most of the paper I concentrate on the simple case in which there is a maximum delay D beyond which the payoff is zero with certainty and below which losses are zero. I define:

$$f^D(d) := \begin{cases} 0 & \text{if } d \leq D \\ -\infty & \text{if } d > D \end{cases}. \quad (5)$$

Example 2 in Section 3 makes clear that the basic results of the paper also hold for the case with a convex and differentiable cost function.

As a measure of firm productivity I use the expected output per unit of time

$$\rho := \frac{\pi}{d} = \frac{nq + a(p - q) - f(d)}{d}. \quad (6)$$

Note that one does not need to normalize for the total workload n because this workload is given exogenously. The surplus per unit of time is denoted by

$$\sigma := \frac{\pi - ac}{d}. \quad (7)$$

Finally, taking into account the number of managers who are busy in the hierarchy (see also Meagher 1997), we may define labor productivity as

$$\varsigma := \frac{\pi - ac}{md}. \quad (8)$$

Iso-probability-of-success lines.

3.2 Preferences and wealth constraints

Agents working in the hierarchy do not care about output per se. They care about their monetary income and derive a disutility from providing effort on initial items. All individuals are wealth constrained: initially principals (the owners of projects) and all agents hold no cash.⁸ Therefore, a contract can only specify how output will be shared in case that the project is a success. Consequently, contracts which provide all agents with proper incentives in exchange for an appropriate entry fee, are not feasible.

The outside payoff of agents is normalized to zero.

3.3 The programmed hierarchy

The processing task is performed by a programmed hierarchy of agents (see Radner 1993, and, for a game theoretic extension Grüner and Schulte 2004). In such a network each information processing act (i.e. an agent reads an initial item or a message from some other agent) takes a given amount of time which is normalized to $\delta > 0$. The programme of the hierarchy specifies at which date an agent is supposed to handle an item. Moreover, the hierarchy describes a reporting structure. For simplicity, I assume that any report

⁸Relaxing the simplifying assumption that all agents hold zero wealth would permit to study the relationship between the wealth distribution and the organizational structure.

Figure 1: Two hierarchies with 1 (2) agents and 4 objects with delay 4(3).

about the aggregate of information items from a lower hierarchy level can directly be understood by the superior. Reading the aggregate of several information items only consumes time δ and does not require effort.⁹

Figure 2 displays two organizations that aggregate four information items. The first one consists of one agent who reads all four items and produces with delay 4δ . The second one consists of two agents who read two items each. It produces with delay 3δ .

The programmed hierarchy in combination with the incentive scheme lead to an extensive form game. In this game, a player's strategy fixes how many times an agent provides extra effort on his initial items. Note that only players who handle initial items have to make such an effort choice - all other agents always provide normal effort¹⁰. The solution concept is Nash equilibrium. Given the simple additive structure of the output function (1), an agent provides extra effort in equilibrium if and only if his variable share of output α_i is larger than $c/(p - q)$.

An improvement of ICT efficiency is modeled as an exogenous reduction of the delay δ .

⁹This assumption is made for simplicity. All results of this paper hold if one imposes a cost of effort for the processing of aggregates as well. Grüner and Schulte (2004) analyze this case in detail. The introduction of effort costs on higher levels leads of the hierarchy makes it somewhat more difficult to characterize equilibrium effort levels. The corresponding arguments are not of central importance in the present paper.

¹⁰Grüner and Schulte (2004) explicitly model the reporting space of agents. This leads to a richer possible history of the game and a more complex strategy space. The corresponding arguments are not central in the present analysis.

4 ICT innovations and productivity gains

4.1 Example 1

It is instructive to first consider an example in which the principal uses an equal sharing contract. This contract pays each of the m managers the same fraction α/m of total output¹¹:

$$y_i = \frac{\alpha}{m}x, \quad \alpha \in [0, 1]. \quad (9)$$

Consider a team that has to work on $n = 4$ items. Suppose that there is a maximum delay D beyond which the payoff is zero with certainty, i.e. let $f(d) = f^D(d)$. Fix $D = 4$ and $\delta = 1 + \varepsilon$. Figure 3 displays two corresponding iso-success-probability lines. The two horizontal iso-success-probability curves become vertical at $d = D$. The two straight lines represent the value added (in terms of success probability) that is generated by a single agent who does $(p \cdot d)$ or does not provide $(q \cdot d)$ effort. The principal maximizes expected profits measured by

$$\Pi = \pi - E(t) \quad (10)$$

where $E(t) = E\left(\frac{\alpha x}{m}\right)$ denotes expected transfers to the agent(s). He has to consider two options. One option is to divide the task evenly among two agents. Both agents then simultaneously read two objects. This yields a delay of 2δ . Next one agent sends a report to his colleague which yields a total delay of $3\delta < 4$ (point A in figure 3). There is an incentive contract such that both agents provide effort if

$$\frac{1}{2}(p - q) \geq c. \quad (11)$$

If instead c is above this threshold there is no way to decentralize the task efficiently. The second option is that one agent performs the task alone. The corresponding delay is $4\delta > D$ (point B). Hence, centralization is no good option. At $\delta = 1 + \varepsilon$ the optimal organization decentralizes the processing task, and the delay is $3\delta < 4$. At costs $c > \frac{1}{2}(p - q)$ both agents do not provide effort in the profit maximizing hierarchy.

Next consider an improvement in information technology that reduces delay of a single processing step to $\delta = 1 - \varepsilon$. Centralization now works sufficiently fast because $4\delta < D$ (point C in figure 3). Effort is provided if

¹¹Equal sharing arises when hard incentives are excluded and when success is a publicly provided private good.

$$p - q \geq c. \quad (12)$$

Assume now that

$$p - q \geq c > \frac{1}{2} (p - q). \quad (13)$$

For sufficiently small values of q , the profit maximizing hierarchy works with only one manager. He is in charge of the entire project. His incentive payment t ensures that $(p - q)t > c$. The agent is willing to participate since $4p\frac{c}{(p-q)} - 4c > 0$. Profits are $4p\left(1 - \frac{c}{p-q}\right) > 0$. This is more than $4q$ if $p\left(1 - \frac{c}{p-q}\right) > q$. Under the new contract expected output rises from $4q$ to $4p$ and delay increases from $3(1 + \varepsilon)$ to $4(1 - \varepsilon)$. The firm's output per period changes from $\frac{4q}{3(1+\varepsilon)}$ to $\frac{p}{1-\varepsilon}$. The surplus per unit of time goes from $\sigma = \frac{4q}{3(1+\varepsilon)}$ to $\frac{p-c}{1-\varepsilon}$.

One can now easily verify that marginal ICT improvements may result in significant productivity gains. Take as an example the case where c is slightly above $p/2$ and q is close to zero. The surplus per unit of time before restructuring is close to zero while, after restructuring, it is approximately $4(p - c) \approx 2p$. The previous results can be summarized as follows:

Proposition 1 *There are parameters (n, c, p, q, D, δ) such that marginal improvements of ICT efficiency may result in (i) positive productivity gains measured by ρ and σ , and ς (ii) positive increases of profits, and (iii) a reduced number of hierarchy layers and employees.*

4.2 Example 2: convex cost

The purpose of the second example is to show that our previous results do not rest on the particular non-continuous cost structure that we considered in Example 1. They may also obtain when the cost of delay function is differentiable and convex. Consider again an environment with four items but with a convex cost function $f(d)$ with

$$f'(0) = 0, \quad f''(d) > 0. \quad (14)$$

Again assume that

$$p - q \geq c > \frac{1}{2} (p - q). \quad (15)$$

Figure 4 explains why the outcomes from Example 1 may also realize with convex costs. The figure displays two iso-success-probability lines. Suppose that the initial delay per unit is $\delta = 1$. The two straight lines represent the value added (in terms of success probability) which is generated by a single agent who does $(p \cdot d)$ or does not provide $(q \cdot d)$

Figure 2: Example 1.

effort. Consider the case in which q is so low that the probability of success of a reduced tree with two agents is zero (point A in figure 4):

$$q = \frac{f(3)}{4}. \quad (16)$$

Moreover, assume that a single agent does not produce a positive probability of success: $4p - f(4) = \varepsilon < 0$ (point B). After an ICT improvement the optimal hierarchy is a single agent hierarchy (point C). The probability of success is

$$\pi = 4p - f(4\delta). \quad (17)$$

Expected profits are:

$$\Pi = 4p \left(1 - \frac{c}{p-q} \right) - f(4\delta). \quad (18)$$

Before restructuring the surplus per unit of time is given by:

$$\sigma = \frac{\pi - ac}{d} = \frac{0}{3} = 0. \quad (19)$$

After restructuring it is:

Figure 3: Example 2

$$\sigma = \frac{4p - f(4\delta) - 4c}{4} = p - c - \frac{f(4\delta)}{4}. \quad (20)$$

Figure 4 characterizes a situation in which the new hierarchy generates a higher surplus. Point D in figure 3 corresponds to a situation in which the old hierarchy is kept while ICT improves. The convexity of $f(\cdot)$ guarantees that there is an extra gain in the probability of success that is due to the restructuring process. Points E and F identify the combinations of surplus and delay that are realized in the two different hierarchies. As one can easily verify, the surplus per unit of time is larger when the task is delegated to a single agent. Again, a marginal ICT improvements may result in significant productivity gains.

5 Optimal hierarchies

5.1 The reduced tree

In this section, I derive two more general results about the optimal hierarchy design for the case of an equal sharing rule. Under an equal sharing rule the optimal hierarchy can easily be determined. It has the form of a reduced tree as described in Radner (1993). The

Figure 4: Two programmed hierarchies with 4 processors and 12 items.

reduced tree is the hierarchy which minimizes the delay for a given number of objects and agents. It can be constructed as follows. All managers are numbered consecutively from 1 to m . Each manager is assigned the same number of initial items. If there are single leftover objects, then the remaining items are distributed in such a way that no manager handles more than one additional item. After reading their initial objects, managers with an even ordering number x report to manager $x - 1$. After that the procedure is repeated with the remaining managers until the final result is obtained by manager 1.

Radner studied efficient organizations along the dimensions delay (d), number of managers (m) and number of items (n). He found that any efficient network is a reduced tree. Figure 5 provides an example of a reorganization that leads to less delay for a given number of processors. Figure 6 provides an example for the construction of a reduced tree with 8 processors and 24 items.

5.2 Optimal hierarchy

I consider the case where $f(d) = f^D(d)$. Two definitions are useful. Agents have less incentive to provide effort if the number of managers increases. Managers can only be induced to provide effort if $p - q/m > c$. Therefore one may define:

Definition 1 Call $m^e = \lfloor (p - q) / c \rfloor$ the largest number of managers for which there is a full effort equilibrium under an equal distribution of revenues.

Figure 5: Construction of a reduced tree with 8 processors.

A delay of less than D requires a minimum number of managers instead. I define:

Definition 2 Let $f(d) = f^D(d)$. Call $m^d(n, \delta, D)$ the smallest number of managers necessary to process n objects with a delay of less than D .

The optimal hierarchy design depends on the relation of m^d and m^e .

Proposition 2 Consider a hierarchy working under an equal sharing rule and let $f(d) = f^D(d)$.

- (i) Let $m^d(n, \delta, D) = m^e$. A reduced tree with $m^d = m^e$ managers maximizes the probability of success. All managers in this hierarchy provide effort.
- (ii) Let $m^d > m^e$. Every hierarchy which produces with a delay of less than D maximizes the probability of success. Any hierarchy which maximizes the probability of success does not induce effort.
- (iii) Let $m^d < m^e$. There is a full effort reduced tree which maximizes the probability of success for any number of managers m with $m^d \leq m \leq m^e$. All these hierarchies yield full effort and an identical probability of success.

Proof (i) According to Radner 1993, Theorem 1, any faster hierarchy uses more managers for the given number of items. These managers have no incentive to provide effort. Any slower hierarchy takes too long for its processing task and the corresponding surplus would be zero. Any hierarchy with the same number of managers creates at most the same profit but cannot work faster. Parts (ii) and (iii) are obvious. *Q.E.D.*

Note that in cases (ii) and (iii) the hierarchy which maximizes the surplus is uniquely defined when normal effort is costly.

For small values of q Proposition 1 also describes the profit maximizing hierarchy. For any given set of parameters (p, c) the hierarchy which maximizes the probability of success

also maximizes profits when q is sufficiently close to zero. This is so because the hierarchy that maximizes the probability of success always generates non-negative profits whereas the no-effort hierarchy generates the high return with a probability which can be made arbitrarily close to zero.

A consequence of Proposition 1 is that ICT improvements are likely to lead to a reduction of the number of hierarchy layers (measured by the highest number of superiors of all agents in the hierarchy). The reason is that without any institutional change delay is reduced. Reducing the number of hierarchy layers has the potential of increasing incentives without sacrificing too much delay.

Meagher (1996) has pointed out that, for a given number of items, the number of layers in optimal hierarchies need not be unique. The following proposition takes this into account and discusses the behavior of the lower bound on the number of layers in optimal hierarchies. I call the minimum number of hierarchy layers the smallest number of hierarchy layers of any hierarchy maximizing the probability of success.

Proposition 3 *Let $f(d) = f^D(d)$. An increase in ICT productivity never increases the minimum surplus maximizing number of hierarchy layers. When $m^d < m^e$ a sufficiently strong increase in ICT productivity decreases the minimum number of hierarchy layers.*

Proof An increase in ICT efficiency weakly reduces m^d . The rest is a corollary of the previous proposition and Radner (1993). *Q.E.D.*

Note that this result differs from Garicano (2000). In his model improvements in the processing technology tend to increase the number of hierarchy layers because the cost of the decentralization of knowledge declines. A consequence of the present result is that the optimal change of the organizational structure may be drastic in the sense that hierarchy levels may disappear and that a huge fraction of the employees may have to be dismissed. This holds for arbitrarily large hierarchies.

Observation 1 *For all $k \in N$ and $n = 2^{k+j}$ with $j \in N \setminus \{1\}$ there are values c , D , and δ such that (i) the profit maximizing hierarchy works with $m = 2^k$ managers and (ii) profit maximizing restructuring after a marginal increase in IT productivity includes that one hierarchy layer is skipped and half of the old employees are no longer employed.*

Proof First fix D , and δ so that $D/\delta = k + j + \varepsilon$ where $\varepsilon > 0$. In this case $m^d(n, \delta, D) = 2^k$. Next fix c so that $c = (p - q)/2^{k-1} > (p - q)/2^k$. The optimal hierarchy works with 2^k managers who do not provide effort. At $\varepsilon = 0$ a hierarchy with 2^{k-1} managers provides effort, is sufficiently fast and maximizes profits. *Q.E.D.*

Note that the last results does not depend upon the particular formulation of the cost of delay function $f(d)$. One can easily verify that a convex and continuous cost function may also permit observation 1.

6 Unrestricted sharing rules

So far I have assumed that the principal has to share the output of $x = 1$ equally among all agents. This is restrictive because the principal can remunerate different agents differently when a full effort equilibrium is not available under equal sharing. I now consider the more general case. An incentive contract fixes the output share $\alpha_i \in [0, 1]$ of each agent and an up front payment to the agent $\bar{y}_i \geq 0$. An agent either provides effort on all his objects or on none of them. He provides effort if his share α_i satisfies

$$\alpha_i(p - q) \geq c. \quad (21)$$

It may now be optimal to provide only some agents with incentives. This ensures that those agents work hard on his initial items. The remaining agents only provide normal effort on their items.

Observation 2 *With an unrestricted sharing rule it may be the case that*

(i) before the improvement of ICT efficiency some employees get an incentive payment and work hard while others do not.

(ii) after restructuring the hierarchy has less layers and less employees, incentive payments are made to all employees, and all agents provide first best effort.

Proof It suffices to provide an example. Consider again the first example from section 3. For large enough values of c , there is no full effort equilibrium contract in the decentralized organization with two agents. One option is not to provide any incentives to both agents and to realize profits of $4q$. However, at low values of q it pays to fix $\alpha_1 = c/(p - q)$ and $\alpha_2 = 0$ instead. In this case agent 1 provides effort while agent 2 does not. The delay is below D and the surplus is $2p + 2q$. Profits amount to $(2p + 2q)(1 - c/(p - q))$ which exceeds $4q$ when q is small enough. Reducing δ slightly may make it possible to delegate the entire task to one agent who then provides full effort and works with a sufficiently small delay. *Q.E.D.*

This last observation is related to an important feature of many real world organizations. Hard incentives are only provided to some employees - mostly executives - while

others (PA's, secretaries) who also provide relevant input are working on a fixed salary. In such cases ICT innovations enable the principal to reduce the division of labor in the organization and to provide all the remaining employees with proper incentives.

Another interesting observation is that, which general sharing rules, the profit maximizing hierarchy need not be a reduced tree. To see why consider an example where information processing by a single agent creates an excessive delay while splitting the tasks equally is not needed to finish in time. In this case, an unequal split of tasks, combined with unequal incentives may be the profit maximizing organization. The agent who works under incentives only delegates what is needed to finish the tasks in time and provides effort on the remaining tasks.

7 Macroeconomic consequences

We have so far established that a proper reorganization of business enterprises may significantly enhance the productivity effect of ICT innovations. In principle the resulting welfare gain could be used to make everybody better off. Can it be that some economies systematically forgo some of the welfare gains which are associated with a restructuring of their business firms? In this section I study a simple macroeconomic extension of the previous model in order to address this question. I begin with the analysis of equal sharing rules and then discuss the somewhat more complex case of general sharing rules.

The model focuses on the distribution of rents in an economy in which several investment projects are carried out. I assume that there are two types of agents: a number of E entrepreneurs (principals) and M managers. Each entrepreneur has access to the same number $P \geq 1$ of potential projects. All projects have the same size n . The total numbers of entrepreneurs, the number of managers and the number of available projects $E \cdot P$ is fixed. Again, for simplicity I assume that principals have to stick to an equal sharing rule when they design incentive contracts for managers.

Entrepreneurs use incentive contracts in order to motivate their managers to provide effort in their productive relationship. Every incentive contract in combination with equilibrium effort determines the equilibrium surplus which is generated in each firm. The surplus is divided into the entrepreneur's and managers' rents. We define w as the expected equilibrium rent per employed manager (wage minus cost of effort) and r as the expected equilibrium income of a principal. Similar to Legros and Newman (2000) an equilibrium is defined as follows:

Definition 3 *An equilibrium consists of*

- (i) a hierarchy H of size m ,
 - (ii) an incentive contract C ,
 - (iii) wage w per worker and rent r per project, and
 - (iv) an allocation of managers to entrepreneurs' projects
- such that

(a) hierarchy H with contract C maximizes the entrepreneurs' profits subject to agents' participation and incentive constraints.

(b) labor rent w and principal's rent r obtain in a hierarchy of size m , working under incentive contract C .

Before we analyze the distributional consequences of restructuring, we need to verify that an equilibrium generally exists. Consider the hierarchy that maximizes the expected profit of a single project when managers outside option is a zero wage. Suppose that this hierarchy employs m^* managers and let $E \cdot P \cdot m^* < M$. There is an equilibrium in which all entrepreneurs choose this profit maximizing hierarchy and make positive profits with all their projects. Some $(M - EPm^*)$ agents are unemployed. When managers in the profit maximizing hierarchy do not provide effort they obtain zero payoffs in equilibrium. Otherwise they get exactly what is needed in order to guarantee that effort is provided because managers are abundant and some are unemployed.

If instead $E \cdot P \cdot m^* > M$ workers are scarce in equilibrium. All workers are employed in surplus-maximizing firms and entrepreneurs' rents must be equal to zero. One can easily verify that both equilibria are unique when they exist.

Consider now a restructuring process which reduces the number of agents that work on a particular project. Such a restructuring process increases the number of projects that can be carried out successfully in the economy. It may therefore be the case that efficient restructuring leads to a situation in which projects become scarce while managers become abundant. Consequently, the distribution of rents in the economy may be strongly affected by the restructuring process.

Proposition 4 *Consider an economy in a low effort equilibrium in which in all existing firms employ $m > 1$ agents. Let $2EP > M > EP$ and $M/m \in \mathbb{N}$.*

- (i) *In equilibrium $w = \frac{nq}{m} > 0 = r$.*
- (ii) *There is an improvement in IC technology such that in the new equilibrium less managers work in every hierarchy, providing effort. In the new equilibrium capitalists' rents are positive. The rent of all employed managers declines. Moreover, managers' aggregate rents may decline.*

Proof (i) In equilibrium there are not enough managers in order to endow all EP projects with more than one worker because $2EP > M$. Therefore equilibrium rents of principals must be zero. All rents go to managers. All managers have to earn the same share $\frac{nq}{m}$ of the rent generated in a firm. (ii) There always is a reduction of δ so that the surplus maximizing hierarchy turns out to be one in which full effort is provided. In deed, as δ goes to zero, all projects will optimally be carried out by single agents who provide effort and maximize the probability of success. An equilibrium in which all projects are carried out by single managers exists. Some managers are unemployed. In this equilibrium only the incentive constraint and the participation constraint of managers need to hold.

In the aggregate managers on a single project get lower rents than before. An employed manager's payoff is

$$np \frac{c}{p-q} - nc = n \frac{q}{p-q} c. \quad (22)$$

Before, the surplus per firm was nq . The rent of all managers in a single firm always declines since:

$$nq > \frac{q}{p-q} nc \Leftrightarrow p - q > c. \quad (23)$$

One can easily find cases in which the aggregate (and average) rents of managers in the economy are also reduced. This is the case when the total number of firms does not increase too strongly. Before restructuring there are M/m firms, after restructuring $EP < M$ firms. Hence, aggregate rents of managers decline when M is close enough to EPm . *Q.E.D.*

Restructuring does not eliminate all managers' rents. A single manager who provides effort still obtains a payoff of $n \frac{q}{p-q} c > 0$. This is less than what employed managers earned before. However, the number of employed managers also increases. The net effect on expected income is negative when the number of projects does not increase too strongly.

With general sharing rules, the equilibrium with excess supply of projects is different. In this equilibrium, workers who provide effort must have the same payoff as workers who do not provide effort. Otherwise, firms could make money on projects that have not been realized by overbidding the wages of low effort managers in other companies. The equilibrium with excess supply of labor also changes. It is the one in which firms carry out profit maximizing projects which may include that workers are treated differently. Nevertheless, the rent-shifting argument from above remains intact if one reduces delay δ strongly enough.

The above macroeconomic extension of our basic model points out that economies in which managers (or, where appropriate, employed workers) are more powerful are

less likely to implement the necessary efficiency-enhancing structural reforms in business enterprises. When firms are not restructured managers are likely to capture the increase of surplus because they are scarce. After restructuring managers are abundant and their rents will decline instead. Only a compensation of all managers for the restructuring process may yield a solution to this problem.¹²

8 Conclusion

8.1 Related evidence

The paper provides an explanation for the productivity puzzle. ICT improvements and organizational restructuring are highly complementary. An ICT improvement enables employees to perform more complex tasks alone or in small teams. The principal can then solve incentive problems more easily with an appropriate incentive scheme. The number of employees is reduced drastically in such a process.

Europe is well known for rigid labor markets and in particular for high firing costs. This raises restructuring costs and may explain part of the productivity puzzle. The restructuring process also entails a reduced division of labor. Hence, status concerns of employees who are supposed to take over tasks of their subordinates may yield additional management opposition.¹³ These results indicate that IT-induced restructuring may not be in managers' or workers' interest unless appropriate compensatory payments are made. Otherwise management or labor will favor a restrictive regulation that raises the costs of restructuring processes.

The present theory is consistent with a number of recent macroeconomic and microeconomic observations. First, productivity per hour worked is higher in the US than in Europe. This is a feature of the current model when workers' time input is measured by the number of operations which are performed in the hierarchy. Second, the individual workload is larger in the optimal hierarchy which corresponds well to the fact that in the US worktime is larger.

The paper is also in line with recent micro-data on the development of hierarchies

¹²Fernandez and Rodrik (1991) have pointed out some of the difficulties that are associated with such compensation packages. A particular problem is that the credibility of any promised transfer is low when political power is on the side of the agents that capture the rents.

¹³There is anecdotal evidence that some executives refuse to use software such as powerpoint and prefer to give handwritings to secretaries or PAs. Others do not have an own email account but prefer to send or receive emails through their secretary.

in US business companies. In an analysis of a panel of about 300 publicly traded firms Rajan and Wulf (2003) find that in those companies about 25 % of the layers of intermediate management have on average been removed between 1986 and 1999. In the United States, the decline in the average size of firms, as measured by employment, has been well-documented. Brynjolfsson et al (1994) find broad evidence that investment in information technology is significantly associated with subsequent decreases in the average size of firms.¹⁴¹⁵ Most importantly Bresnahan et. al. (2002) find evidence of complementarities among information technology and workplace reorganization in factor demand and productivity regressions.¹⁶ A recent paper by Bloom, Garicano, Sadun, and Van Reenen (2009) has some evidence that ICT innovations may increase the span of control of managers. This is in line with the results of the present paper.

8.2 ICT innovations at the beginning of the 20th century

Chandler (1977) has carefully studied another historical episode in which ICT improvements have come along with the significant restructuring of many companies. He argues that the development of new IC technologies at the end of the 19th and the beginning of the 20th century has led to the development of larger international companies with more employees.¹⁷ The stylized facts of Chandler's analysis seem to be incompatible with some of the the predictions of the present paper and with the more recent data discussed above. How can one explain that the information technology innovations at the beginning of the 20th century had such a different impact on hierarchy designs?

In order to better understand these differences it is first useful to note that the present paper deals with single information processing tasks that need not necessarily occupy all

¹⁴See also Brynjolfsson and Hitt (2000) for an extensive review.

¹⁵Delmastro (2002) instead finds that the use of internal communication networks such as LAN is positively associated with the number of layers in Italian firms.

¹⁶More recent data suggests that employment in the US became again more concentrated in large firms over the last decade. This recent trend need not contradict the present theory. According to the results of this paper, after restructuring less managers should work on single projects within firms and each project should occupy less hierarchy layers. Obviously, this need not involve a reduction of the total size of business enterprises.

¹⁷See Meagher (2003) for a formal model that produces results which are in line with Chandler's empirical analysis. Meagher considers a hierarchy that pays efficiency wages. A larger number of subordinates makes monitoring more difficult for individual managers. This effect limits the horizontal size of the hierarchy (the span of control). On the other hand, steeper hierarchies increase delay. An improvement of ICT may then trigger an increase of the size of the hierarchy.

employees of a single firm. Therefore, hierarchies in this paper need not necessarily coincide with firms. A firm may well consist of several (connected) hierarchies that simultaneously deal with different items (such as a multi-product firm in which different teams work on different products). Information technology improvements may then reduce the size of these smaller hierarchies while affecting the overall size of the company differently.

Many US firms have in deed reduced the number of hierarchy layers at the end of the twentieth century and that the number of employees have also declined. This has been different at the end of the 19th century. One explanation for these differences is that the nature of many production processes has changed over the last one hundred years. The information technology improvements of the end of the ninetieth century have made it possible to control larger firms that operate in multiple countries without losing too much time (Meagher 2003). This way, economies of scale and scope could be better exploited. One explanation for the differential impact of ICT innovations on hierarchy structure is that these economies of scale and scope have meanwhile mostly been exhausted while there is still scope for an improvement of individual information aggregation processes.

8.3 Further research

An interesting option for a deeper empirical analysis of the present theory is to study the differences in the structural adjustment to ICT improvements in firms in Europe and the US. Such an analysis could rely on occupational statistics that are widely available from sources such as the ILO or the ISSP survey programme. The testable hypothesis is that countries in which occupational shares react less flexible exhibit lower productivity levels and growth rates. An alternative option is to collect micro-data on the composition and organizational structure of firms and on their performance. Recently, Bloom et al (2007) have provided evidence that European plants which are owned by American firms use IT more effectively than purely European ones. This indicates that - besides regulation - management style may play a major role in restructuring processes.

The present theory also points out that trade union power may be associated with the organizational structure of firms. It would also worthwhile to study this link using data on trade union power (such as membership rates, labor turnover costs, or the share of workers covered by collective bargaining arrangements) and the hierarchy design. According to the present theory, trade union power should be negatively associated with delayering and dismissal.¹⁸ Such an analysis requires data on the extent of delayering in various sectors

¹⁸A more indirect approach would be to link trade union power and labor productivity. A look at OECD data shows that the share of workers covered by collective bargaining arrangements is not negatively

and countries. However, sample restrictions make it difficult to use some of the existing data¹⁹ for our purposes. Another option would be to use country wide averages of the firm size. But this would be problematic because countries differ in their sectoral structure and sectors differ in average firm sizes. Hence, this research requires the construction of new, multi-country, representative and sector-specific datasets.

Some extensions of the present theoretical framework are also worth being explored. The paper has considered an economy in which a given set of one shot tasks (with given size) can be performed by a hierarchy. Costs of delay are L-shaped in most of the examples and I consider binary effort. These modelling choices are stark. Relaxing some of these assumptions will most likely produce additional interesting results. I would like to discuss a few such modelling choices.

One option is to allow that single firms perform multiple tasks of varying size potentially involving economies of scale or scope. Including the present model into a richer framework where the size and scope of entire companies is analyzed is an interesting option for further research. One way of explaining why technology innovations have triggered such different restructuring processes in the 19th and in the 20th century is that economies of scale have meanwhile been exhausted. Another one (pointed out by an associate editor) is that the nature of many occupations or the technology in general has evolved. It is an interesting task to develop a unified framework that allows to understand both historical episodes.

Another interesting modelling alternative is to consider the case in which tasks arrive periodically at some rate. As has been shown by van Zandt (1997,8) this may yield a different shape of efficient institutions. Balanced hierarchies become more advantageous because different hierarchy layers can simultaneously work on different waves of items. Nevertheless, one can construct examples in which the message of the present paper remains intact when items arrive periodically (see the appendix for such an example). A deeper analysis of this issue along the lines of van Zandt (1997,1998) and Orbay (2002) may provide some additional interesting insights. The general equilibrium version of the present model can also be extended into various directions. One important task is to endogenize agents' occupational choice. Another one is to take heterogeneity of agents into account.

associated with labor productivity. However, one has to take into account that labor productivity should also be related to wages, employment, and productivity for different, more obvious reasons.

¹⁹e.g. Bloom, Sadun, and Van Reenen (2009) and Beck, Asli Demircuc-Kunt, Laeven, and Levine (2008).

9 Appendix: Sequential arrival of information

Consider a situation in which aggregation tasks are performed sequentially. As has been shown by van Zandt (1997, 1998) in this case balanced hierarchies in which superiors do not deal with initial objects may be efficient. These hierarchies permit that the hierarchy simultaneously works on two or more information aggregation task. In this appendix I provide an example in which - under sequential arrival - the basic insights from section 3 remain intact.

Consider an information aggregation task with four items. Let $D = 3.9$ and $\delta = 1$. Suppose that there is an abundant quantity of tasks that may be processed. What is the efficient hierarchy design? A single decision maker is not fast enough. He produces an excessive delay of 4 and can not generate positive profits. The same holds for a balanced hierarchy of three agents. The only remaining option is the reduced tree with two agents. This hierarchy processes a new aggregation task every 3 units of time.

Suppose now that sharing the surplus among two agents yields no incentives. A reduction of δ to 0.9 makes the single decision maker and the balanced hierarchy work with delay $3.6 < 3.9$. The balanced hierarchy processes twice as many tasks per unit of time as the single decision maker. However, only the single decision maker provides effort. The per unit of time surplus he generates is $4(p - c)/3.6$, and for the balanced hierarchy $(4q - 4c)/1.8$. The single decision maker performs better if $p > 2q - c$. Note that there are values p, q , and c such that this condition is compatible with the two incentive constraints of a one- and a two agent hierarchy, $2c > p - q > c$.

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