Information Processing and Technological Progress

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Abstract: This note analyzes the problem of a decision-maker (she) who delegates processing tasks to agents before deciding which projects to implement. We analyze how her organization should be structured given the agents' productivity and wages. Our results show that *i)* worsening economic conditions induce organizations to become "flatter" and *ii)* technological progress can either generate job creation (if productivity is initially low) or job destruction (if productivity is initially high).

1 Introduction

The recent literature on information processing shows how organizations should be set up. In this note, we argue that this information processing approach also sheds light on other aspects of economic activity. More precisely, we focus on the effects of wage variations (whic proxy external economic conditions, see below) and, more interestingly, of technological progress on employment and on the shape of the organization.

To illustrate these points, we develop a simplified model of information processing, in the spirit of Bolton and Dewatripont (1994) Radner (1993), and Radner and Van Zandt (1992), in which we introduce wages[1] and a measure of the agents' productivity. Within this simple framework, we show why technological progress can create or reduce employment, and why organizations should become "flatter" when economic conditions worsen.[2]

Note that the linkages between technological progress and employment are not always clear. In the endogenous growth literature, technological progress generates an expansion in economic activity, and hence in employment or in wages –albeit for technological obsolescence reasons– (see e.g. Grossman and Helpman 1991, or Aghion and Howitt 1997). In some cases, technological progress can also generate a "skill bias" and only favor some fringes of the

[1] Prat (1997) shows that organizations should be pyramidal if wages are convex in human capital. Here, we consider only one type of agent (no human capital heterogeneity) and analyze instead the effect of the aggregate wage level on the shape of the organization.

[2] Van Zandt and Radner (2001) and Meagher, Orbay and Van Zandt (2002) study a different –though related– problem, namely that of environmental uncertainty. They show that increasing uncertainty (e.g. on consumers' tastes) may also afffect the shape of the organization.

population (see e.g. Acemoglu 1998). In this note instead, we assume perfectly homogenous agents whose task consists of aggregating information to ease decision-making by the firm's management. Though very simple, this framework helps explain why technological progress might have opposite effects on the profits of the organization and on employment prospects.

2 The Model

Consider a decision-maker (she), who must decide which project(s) to implement. Initially, a large number of options are available to her, and we represent this set of initial options by a continuum of mass M. Within this set, only a few (possibly one) projects (or "items") generate positive value added. By assumption, the value of a "good" item is arbitrarily large, whereas a "bad" item can generate very large losses. Hence, it is optimal to first evaluate the potential return of each item in the set, before deciding which one(s) to implement.

Decision-maker vs. Agents. The decision-maker is the only person who can exactly identify the value of a given project. However, project evaluation is a time-consuming task, and the principal may thus benefit from the help of external agents. Agents, on their side, only imperfectly assess the decision-makers' valuation of the projects. We interpret their task as follows: with some probability $(1 - f)$, the agent identifies a project as being "irrelevant" for the principal, and hence discards it. In contrast, agents never mistake "good" projects for "bad" ones.

Hierarchy. To coordinate agents, the decision-maker creates a hierarchy, which is structured into *layers*, denoted by $l = 0, ..., L$. In such a hierarchy, the initial set (M) must be processed first in layer L, then in layer $L-1$, $L-2$, and so on until the top of the hierarchy (the decision-maker, in layer 0) is reached.[3] By the law of large numbers, each agent removes exactly a fraction $(1 - f)$ from the set he works on, and only transmits the remaining fraction f to his *superior*. The mass of items reaching layer l is thus equal to $M \times f^{L-l}$.

The decision-maker can freely organize her hierarchy: she controls both the number of layers L and the number of agents in each layer, n_l. The only constraint she faces is that the agents' work must be coordinated, so that tasks are not duplicated. We introduce coordination (or "communication") costs by assuming that each agent slows down the hierarchy by a fixed delay λ, in addition to the time he works. Next, following Bolton and Dewatripont (1994), the time needed to process a given amount of information is proportional to the mass

[3] We do not allow for "skip-level reporting" (See Radner 1993).

of information to be processed, and we normalize to m_i units of time the delay needed by a person i (agent or principal) to process a mass m_i of information items.

Hence, the *delay* (D) needed to reach a decision in a hierarchy with L layers and n_l agents in each layer becomes:[4]

$$D\left(L,\{n_l\}\right)=\sum_{l=1}^{L}\left(M\frac{f^{L-l}}{n_l}+\lambda n_l\right)+M\,f^{L}. \tag{1}$$

That is, the agents in layer l process (in parallel) a fraction $1/n_l$ of the total mass of information reaching the layer, and the first term in (1) is the total delay imposed by all the agents in all layers, including coordination costs. The second term represents the time needed by the decision-maker to identify which project(s) should be implemented.

Objective function and costs. The objective function of the decision-maker is to reach a decision at minimum cost. Both the time needed to reach a decision and the agents' work are costly. For the sake of tractability, we assume that the marginal cost of delay is constant and equal to r,[5] and that the marginal cost of the time worked by the agents is constant and equal to w: an agent who processes a mass m_i will be paid a wage $w\,m_i$. The total wage bill W thus amounts to:

$$W\left(L,\{n_l\}\right)=w\sum_{l=1}^{L}M\,f^{L-l}.$$

Hence, the objective function of the decision-maker becomes:

$$\min_{L,\{n_l\}}\;TC\left(L,\{n_l\}\right)=r\,D\left(L,\{n_l\}\right)+W\left(L,\{n_l\}\right).$$

3 Optimal Hierarchies

The problem of the principal is thus to create the hierarchy that optimally trades-off processing delays and wage costs. Our first proposition says the following:[6]

[4] We assume that a layer transmits its output only once it has completed *all* its task. Alternatively, one could consider "real time" processing, under which each agent instantly transmits processed items. Such a specification, however, is much less tractable, while it generates similar results (see Sections 3 and 4).

[5] The assumption of a constant marginal cost of delay is certainly unrealistic, but it is sufficient for the purpose of our analysis. In a more general setting, the marginal cost of delay could be represented by any function $r\left(D\right)$, and an increase (respectively decrease) in the marginal cost of delay be captured by setting $\tilde{r}\left(D\right)>r\left(D\right)$ (resp. $\tilde{r}\left(\cdot\right)<r\left(\cdot\right)$), $\forall D$.

[6] Explicit solutions do not exist for real-time processing but generate similar results (hierarchies must be pyramidal, and wages induce smaller and flatter hierarchies).

Proposition 1 *Optimal hierarchies are necessarily pyramidal (i.e.* $n_{l-1} \leq n_l$*). Moreover, the optimal number of agents in a layer is independent of wages, and the optimal number of layers is given by:*

$$L^* = \max\left\{ \left\lceil 2\frac{\log\left(2\sqrt{\lambda/M}\right) - \log\left[(1-f) - w/r\right]}{\log\left[f\right]} \right\rceil, 0 \right\}. \tag{2}$$

That is, it is increasing in M *and in* r*, and decreasing in* w *and in* λ*.*

Proof. Neglecting integer constraints, the optimal number of agents in layer l results from the first order condition:

$$\frac{\partial TC}{\partial n_l} = 0 \;\Leftrightarrow\; n_l^* = \sqrt{f^{L-l}\frac{M}{\lambda}}, \tag{3}$$

which is thus increasing in l and independent of w.

Next, we compare total costs between a hierarchy with L and $L+1$ layers:

$$TC\left(L+1, \{n_l^*\}\right) - TC\left(L, \{n_l^*\}\right) = Mf^L\left(2\sqrt{\lambda/\left(M f^L\right)} + f - 1 + w/r\right).$$

Neglecting integer constraints for now, we derive L^{**} by setting this difference to zero:

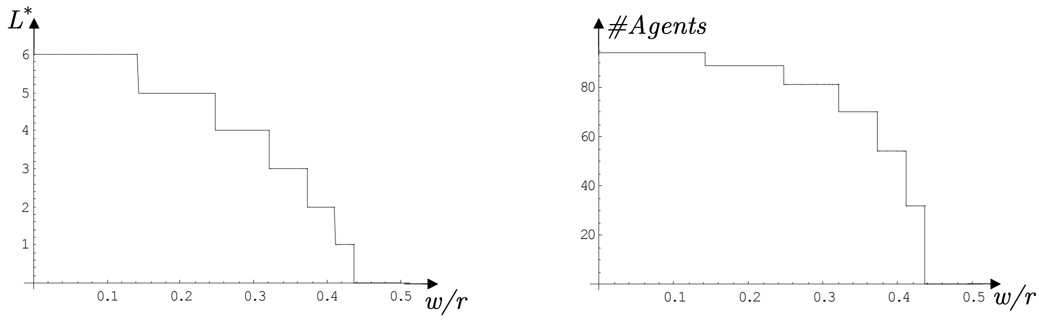
$$L^{**} = 2\frac{\log\left(2\sqrt{\lambda/M}\right) - \log[(1-f) - w/r]}{\log[f]}. \tag{4}$$

Then, reintroducing integer constraints yields (2), where $\lceil\cdot\rceil$ denotes rounding up to the nearest integer. Note also that, from (2), we have: $w/r > 1-f \;\Rightarrow\; L^* = 0$. ■

The first part of Proposition 1 is consistent with the results of the literature (see e.g. Radner and Van Zandt 1992, Radner 1993, Bolton and Dewatripont 1994, Prat 1997, Garicano 2000). More interesting is the effect of the ratio w/r on the shape of the hierarchy: from (3), the optimal number of agents in a given layer is not affected by the level of wages, since total wage costs remain identical if a given amount of work M_l is split between n_l or n_l' agents. Only the optimal number of layers is affected. Therefore, if wages increase or if the opportunity cost of time decreases, only the number of layers is reduced. Finally, if the marginal cost of work w is larger than the agents' nominal productivity $(r(1-f))$, there is no benefit to delegating tasks to agents, in which case there cannot either be employment in that firm. Figure 1 illustrates this graphically.

Such results can clearly be linked to macroeconomic fluctuations: generally, wages only react to economic fluctuations with a lag. Hence, Proposition 1 shows that, when economic activity starts to slow down (r falls, and w remains constant), employment will start falling.

Figure 1: Optimal number of layers and total employment ($M = 2000$; $f = 1/2$)



However, the magnitude of those effects will be small in this early phase (see Figure 1). If economic activity keeps worsening, w/r will keep increasing, and the magnitude of additional layoffs will increase, with the possible shutdown of some companies.

4 The Effects of Technological Progress

The results of Proposition 1 also allow us to analyze the effects of technological progress on employment. We capture the productivity of the agents with the fraction of projects they can discard, $1 - f$: the lower the value of f, the higher is the agents' productivity. Technological progress thus amounts to assuming that f falls over time. Following this terminology, we find:

Proposition 2 *For w/r sufficiently low and M sufficiently large, technological progress displays* ***job creation*** *in the early phases of development (f close to 1), and* ***job destruction*** *in the later phases of development (f close to 0). In the long-run, it generates "flat" hierarchies ($\lim_{f \to 0} L^* = 1$).*

Proof. From (2), we see that $L^* = 0$ for $f \geq 1 - w/r$ and $L^* = 1$ for $f \to 0$. Differentiating (4) with respect to f also shows that $\frac{dL^{**}}{df} < 0$ iff

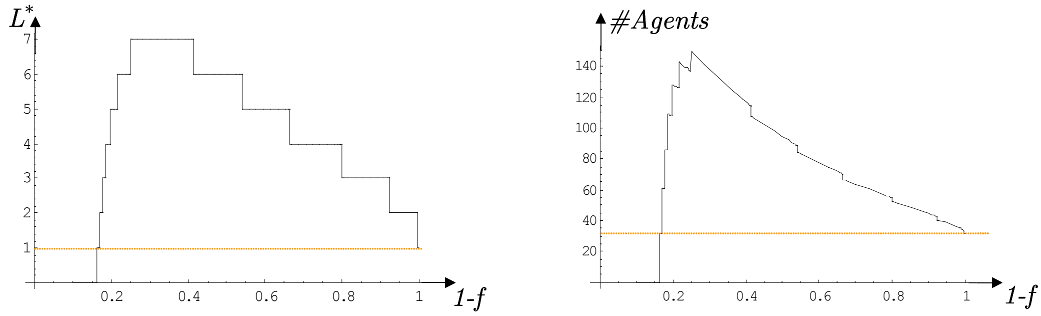
$$(1 - f - w/r)\left(\log\left[2\sqrt{\lambda/M}\right] - \log\left[1 - f - w/r\right]\right) > f\ \log\left[f\right],$$

which is satisfied for $f \to (1 - w/r)$ and violated for $f \to 0$ (note that $\lim_{x \to 0} x\ \log\left[x\right] = 0$). ■

In words, depending on the initial productivity level, technological progress can either be a blessing or a curse for workers. If productivity is initially very low, then technological progress allows the creation of new economic activities, and hence new job opportunities. However, if the agents' productivity is already high, then technological progress is detrimental to employment: the same tasks can be achieved with fewer agents, and in flatter hierarchies (Figure 2 below illustrates those results).[7] Still, total costs decrease in all cases, which means that the decision-maker always benefits from technological progress.

Note also that we are working in a partial equilibrium framework: w is kept exogenous in the model. However, our results would actually be reinforced if we introduced general equilibrium concerns: higher productivity should increase wages, which further reduces employment (from Proposition 1, wage increases tend to reduce delegation and employment).

Figure 2: Optimal number of layers and total employment ($M = 2000$; $w = .1$)



5 Conclusions

This note introduces wages and technological progress in the "classical" models of information flows and hierarchies. In our view, this classical framework provides good microfoundations to model the organizations' activity, and hence address several questions, such as the boundaries of the firms (Castanheira and Leppämäki 2001), or the role of external market conditions and technological progress (this note). In particular, it sheds light on the ambiguous links between technological progress and employment, which cannot be explained by an aggregate production function approach. In future work, we intend to address additional questions, such as the effects of human capital or task complexity.

[7] Results are marginally different under real-time processing: as in our main setup, $f \to 1$ still implies $L^* = 0$ and $f \to 0$ implies $L^* = 1$, and the optimal number of layers and of agents in the hierarchy peaks for intermediate values of f. In contrast to our main setup, however, the optimal number of agents in the hierarchy is not quasi-concave in f anymore.

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