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Adoption and Use of New Information
Technology

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Adoption and Use of New Information Technologies*

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Abstract

A general result of information theory is that asymmetric information generates agent rents and distortions in production. In this paper, we analyse the impact of asymmetric information on adoption and use of information technology (IT). Depending on the contracting scheme, different results may occur. We explore the differences between the case of contractible investment and the case of noncontractible investment. Assuming the investment decision (adoption) as a constraint on the maximal level of production (use), the results for a contractible case are similar to the standard results obtained from the incentive theory. On the other hands for the noncontractible case the results are new for this literature and present some important consequences. The focus on IT is justified by two considerations. First, it is possible to assume that principal has not much information about new technological skills of the agent. Second, adoption decision on IT are strongly related with our hypothesis on the investment modelling. The main thesis of the paper is that with IT costs sufficiently low, incomplete information and noncontractible investment, there is on average both over-investment and under-use of IT. This result is useful to shed light on IT productivity paradox.

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1 Introduction

Recent literature on information technology (IT) has drawn attentions to a paradox: there is no clear link between IT and productivity. Moreover some studies have re-examined this puzzle suggesting that the paradox can depend on modeling techniques and estimation procedures. In particular, Mehmet [1998] proposes a model where strong learning-by-doing effects explain the investment behavior of firms. Lee and Barua [1999] used stochastic production frontier analysis to show that a previous study had significantly underestimated the real contribution of IT.

In this paper we propose a model that may shed some light on the productivity paradox from a theoretical view. The starting point is that the efficacy of an investment depends first of all on the use (or non-use) that employees do. If a technology is very productive but the employee does not use it, its contribution to the output is clearly nil. From our point of view, the puzzle arises from a problem in the measurement of the impact of IT because the empirical studies measure the level of investment and not of the effective use. This hypothesis is confirmed by a recent study (Bergman, Feser and Alexander Kaufmann[1999]). Now it remains to explain why the employees do not use IT and why firms decide to invest never these.

We propose a model of asymmetric information (Mirlees[1971], Baron and Mayerson[1982], Guesnerie and Laffont[1984]), between a principal (the management) and the agent (employees). The principal decides on an investment level and (then or simultaneously) offers the agent a set of incentive compatible contracts. We assume that the principal does not renegotiate the whole work contract but only negotiates on a bonus. Furthermore, it is reasonable to assume that the principal does not know exactly the agent's capabilities on IT. Therefore, she decides to offer an incentive contract. This contract compels the agent on the level of use of IT and consequently on the level of output. Depending on the contract scheme, different results emerge.

We explore the differences between the case of contractible investment and the case of noncontractible investment. When the investment is contractible the result is similar to the one obtained from the standard incentive theory: there is a lower use (and lower investment) and the ratio of distortion grows with the degree of asymmetry. When the investment is notcontractible, the results change drastically showing a discrepancy between investment decision and use. When deciding on the investment level, the principal has no information on the actual needs of the agent, hence she acquires IT expecting it will be used. Therefore, if the cost of IT is sufficiently low, the principal on average invests more than in the previous case (and also than in the case of complete information) with the goal of satisfying as much as possible the requirements of all possible types of agents.

The rest of the paper is organized as follows: in paragraph two we present the hypotheses and the model with complete information, in paragraphs three and four we treat the case of incomplete information with contractible and noncon-

tractible investment respectively. Paragraph five is devoted to the comparison of the results. Concluding remarks are in paragraph six.

2 The Model

The introduction of IT often discloses different capabilities among employees. There are employees that can use it with low effort, whereas others have more difficulties. It is hard for the management (principal) to know if her employees (agent) have these skills or not. Assume that the principal wants to introduce an IT and that she wants to offer an incentive contract to the agent to increase the output. Note that the principal had already negotiated a general contract with the agent and at this stage she negotiates only on changes determined by IT. So, the principal can contract only on an extra bonus for an increase in output with the counterpart. For simplicity, the model focuses only on the increase of output (S) generated by the use of IT. The (extra)output is sold on a competitive market at price p , that it is normalized to one.

We consider the IT investment as a constraint on the agent's possible actions (use of IT). For example, the acquisition of mobile telephone allows to contact employees away from the workplace; dedicated lines allow to link computers in two different buildings that otherwise could not share information, and so on. Formally, the IT investment \bar{q} is modelled as a limitation on the agent's action q : $q \leq \bar{q}$. Its cost is $C(\bar{q})$ where C is a strictly increasing convex function. The agent uses IT (partially or completely) to produce output $S = S(q)$ where S is a strictly increasing concave function; he gets in return a transfer t , and makes an effort ψ . The effort $\psi = \psi(\theta, q)$ depends on his action q and on his type $\theta \in [\underline{\theta}, \bar{\theta}]$ (where $\underline{\theta}$ denotes an agent with high technical skills and $\bar{\theta}$ denotes an agent with low technical skills). Effort function is increasing in both arguments and we have made the supplementary assumptions that $\partial^2 \psi(\theta, q) / \partial \theta^2 > 0$, $\partial^2 \psi(\theta, q) / \partial q^2 > 0$, $\partial^2 \psi(\theta, q) / \partial q \partial \theta > 0$, $\partial^3 \psi(\theta, q) / \partial q \partial \theta \partial \theta > 0$ and $\partial^3 \psi(\theta, q) / \partial q \partial \theta \partial q > 0$. The distribution of types $F(\cdot)$ has a monotone hazard rate $\partial [F(\theta) / f(\theta)] / \partial \theta \geq 0$.

Before stating the first-best solution, we want to dwell briefly on two features of this model related to our assumptions on IT investment. First, the introduction of IT does not automatically increase output; but it needs some commitment on the employees part. Second, IT is essential for the agent to increase output, hence he could not produce more without it, despite his efforts.

The utility of the agent depends positively on the extra-bonus he receives and negatively on his additional effort; we adopt an additive separable utility function (as, e.g., in Kofman and Lawarée[1993]) for analytical convenience:

$$U = t - \psi(\theta, q) \tag{1}$$

The principal's utility is given by her profit:

$$V = S(q) - t - C(\bar{q}) \quad (2)$$

Throughout the paper we assume, for the sake of simplicity, that all the solutions are internal. In case of complete information, the principal solves her optimization problem knowing the type of the agent.

$$\mathbf{P1} \quad \max_{q(\theta), \bar{q}} S(q(\theta)) - C(\bar{q}) - t(\theta). \quad (3)$$

subject to:

$$U(\theta) = t(\theta) - \psi(\theta, q) \geq 0 \quad (i)$$

$$q(\theta) \leq \bar{q} \quad (ii)$$

Here constraint (i) is the participation constraint and constraint (ii) is the investment bound on use. The problem $P1$ can be rewritten in a easier form after these considerations. First, knowing θ , the principal offers a transfer of an amount exactly equal to the reservation payoff to induce the agent's participation and extracts all the rent, hence: $t(\theta) = \psi(\theta, q(\theta))$. Secondly, she can choose the investment level without uncertainty and so fix it exactly equal to the use of the agent: $\bar{q} = q(\theta)$. Hence $P1$ is equivalent to a simpler unbounded optimization problem $P1'$:

$$\mathbf{P1}' \quad \max_{q(\theta)} S(q) - \psi(\theta, q) - C(q). \quad (4)$$

The first order condition is:

$$S'(q) - C'(q) = \psi_q(\theta, q) \quad (5)$$

With the aforementioned assumptions, equation (5) is also a sufficient condition for $P1'$. Hence in a world without informational asymmetries, the agent receives only his reservation payoff and the principal induces an effort level that matches the marginal benefits to the marginal costs. Using Dini's Theorem, we can derive the slope of $q(\theta)$:

$$q'(\theta) = \frac{\psi_{q\theta}(\theta, q)}{S''(q(\theta)) - C'''(q(\theta)) - \psi_{qq}(\theta, q)} \quad (6)$$

As we expected, the level of use, that corresponds to the level of investment, depends negatively on θ .

In case of incomplete information, θ corresponds to the agent's private information. The revelation principle (see, e.g., Laffont and Tirole[1993]) implies that we can restrict attention to contracts that ensure that an agent truthfully announces his type. In this paper we focus on piecewise differentiable solutions. The principal behaves as a Stackelberg leader offering a contract, in which she has committed herself, specifying \bar{q} , q and t for all possible configurations (θ) reported by the agent. Throughout the paper, we assume that the contract is enforceable. Such contracts are called "incentive compatible" contracts.

3 Contractible Investment

When information asymmetry is present, we distinguish two cases: contractible investment and noncontractible investment. In this paragraph, we consider the first one. In the case of contractible investment the principal can simultaneously contract with the agent on t , q and \bar{q} . Timing of the problem can be summarized as follows:

1. Nature determines θ , then agent knows it.
2. Principal offers a set of incentive compatible contracts including the investment decision $(t(\theta), q(\theta), \bar{q})$ where $\bar{q} \geq q(\theta)$.
3. Agent announces θ , then
4. principal invests $\bar{q} = q(\theta)$ and
5. agent produces $S(q(\theta))$ using $q(\theta)$ IT.
6. Game stops. Agent gets $t(\theta)$, and the principal gets $S(q(\theta)) - t(\theta) - C(\bar{q})$.

The solution of the principal's and the agent's maximization is represented by the following optimization program:

$$\mathbf{P2} \quad \max_{q(\theta), \bar{q}} \int_{\underline{\theta}}^{\bar{\theta}} [S(q(\theta)) - t(\theta)] dF(\theta) - C(\bar{q}) \tag{7}$$

subject to: $\forall \theta$

$$\theta \in \arg \max_{\tilde{\theta}} t(\tilde{\theta}) - \psi(\theta, q(\tilde{\theta})) \tag{i}$$

$$U = t(\theta) - \psi(\theta, q(\theta)) \geq 0 \quad \forall \theta \tag{ii}$$

$$q(\theta) \leq \bar{q} \quad (\text{iii})$$

Constraint (i) is the incentive-compatibility condition, requiring that truth telling be a Bayesian-Nash equilibrium. Constraint (ii) represents a participation constraint reflecting that agent knows his cost prior to contracting. Constraint (iii) is the investment bound on use. This problem is consistent with the standard incentive problems and may be restated as follows (see appendix):

$$\mathbf{P2'} \quad \max_{q(\theta)} \int_{\underline{\theta}}^{\bar{\theta}} \left[S(q(\theta)) - \psi(\theta, q(\theta)) - \frac{F(\theta)}{f(\theta)} \psi_{\theta}(\theta, q(\theta)) \right] dF(\theta) - C(q(\theta)) \quad (8)$$

subject to:

$$q'(\theta) \leq 0 \quad \forall \theta \quad (\text{a})$$

This is a problem of calculus of variations (see, e.g., Kamien and Schwartz [1991]), we solve the problem as if constraint (a) is not binding and then we check. The a first order condition is:

$$S'(q(\theta)) - C'(q(\theta)) = \psi_q(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{q\theta}(\theta, q(\theta)) \quad (9)$$

The Legrende condition ($0 \leq 0$) is respected. Using Dini's theorem we can derive the slope of $q(\theta)$ that is non positive as required by (a):

$$q'(\theta) = \frac{\psi_{q\theta}(\theta, q(\theta)) + \frac{\partial}{\partial \theta} \left[\frac{F(\theta)}{f(\theta)} \right] \psi_{q\theta}(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{q\theta\theta}(\theta, q(\theta))}{S''(q(\theta)) - C''(q(\theta)) - \psi_{qq}(\theta, q(\theta)) - \frac{F(\theta)}{f(\theta)} \psi_{q\theta q}(\theta, q(\theta))} \leq 0 \quad (10)$$

In fact the numerator is positive by assumption on the effort function and the hazard rate and the denominator is negative by the hypothesis on the output function, effort function and the cost function.

As we expected, the introduction of asymmetric information adds an extra term to the solution (compare equation (9) with equation (5)), which induces a reduction of the level of q for each value of θ . In fact, fix θ arbitrarily. In the first order condition for problems $P1$ and $P2$ the left-hand sides (marginal revenue net of IT costs) are the same in both equations and are a decreasing function in q . The right-hand sides of the two equations (marginal payment to the agents) are both increasing functions of q and the term of equation (9) is

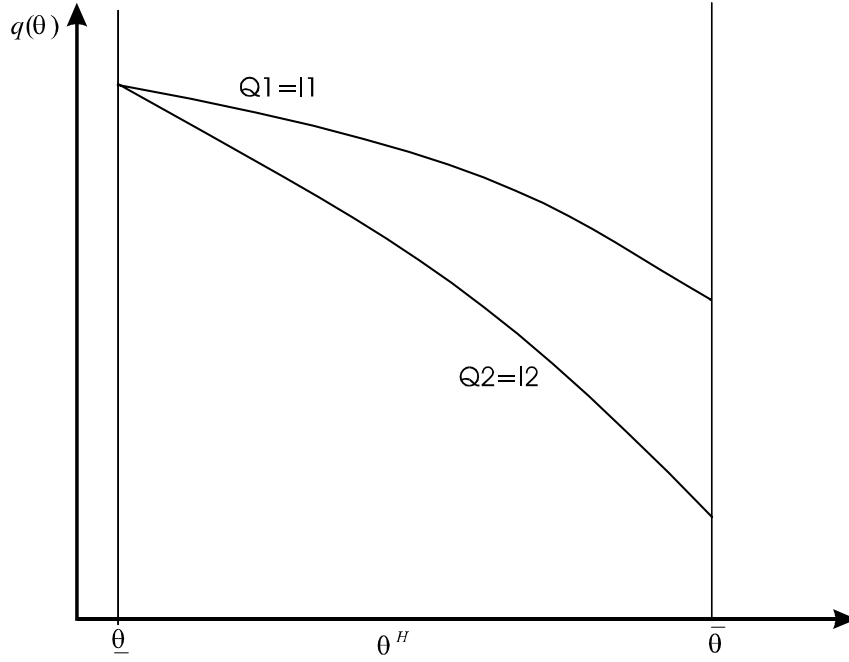


Figure 1: Adoption and use of IT in case of complete information and incomplete information with contractible investment

greater than in (5). Hence, we expect the q of equilibrium in problem $P2$ to be higher than or at least equal to that in $P1$.

Considering also that at $\theta = \underline{\theta}$ the problem $P1$ and $P2$ have the same solution (because the two equations coincide), we have a clear characterization of the solution of these two problems that may be represented in figure 1. We call $Q1$ and $Q2$ respectively the curve that describes the use of IT by agents coming from the solution of problems $P1$ and $P2$; and $I1$ and $I2$ the investment decision of the firm related to $Q1$ and $Q2$. Note that in the case of perfect information or imperfect information with contractible investment these two curves coincide.

4 Noncontractible Investment

In the case of noncontractible investment, there are some discrepancies in the results. Timing of the problem can be summarized as follows:

1. Nature determines θ , then agent knows it.
2. Principal invests \bar{q} , then

3. she offers a set of incentive compatible contracts to the agent considering the restriction imposed by her investment decision: $(t(\theta), q(\theta))$ where $q(\theta) \leq \bar{q}$.
4. Agent announces θ ; then
5. he produces $S(q(\theta))$ using $q(\theta)$ IT.
6. Game stops. Agent gets $t(\theta)$, and the principal gets $S(q(\theta)) - t(\theta) - C(\bar{q})$.

The main difference with the previous case is due to the fact that the principal has to choose the level of IT before knowing the agent's type. We have already shown that, provided there are no bindings, the use of IT increases with the skills of the agent. This means that if the principal wants to offer an incentive contract to high skill agents, she has to invest more in IT (in step 2) than if she wants to offer incentive contracts only to lower skill agents. Given these considerations we can imagine that the principal, to save money, may decide to offer incentive compatible contracts only to a subset of types.

Consider now dividing the agents in three segments. Those with low technological skills $(\theta^L, \bar{\theta}]$, those with intermediate skills $[\theta^H, \theta^L]$ and those with high skills $[\underline{\theta}, \theta^H)$. In a strategy of incentives, the principal can offer a contract not to all segments but only to agents with intermediate skills. Clearly the principal has to choose θ^L and θ^H . If she chooses $\theta^L = \bar{\theta}$ this means that she offers incentives also the lower segment. If not, low skilled agents will not be offered incentives to use IT. On the other side the principal has no interest to offer incentives to agents with high skills (i.e. those who have higher than the required skills), but in any case they can choose the contract offered to θ^H . For the low skill segment $(\theta^L, \bar{\theta}]$, the principal offers a contract that ask to produce nothing, giving nothing in return, so the participation constraint is respected. For high skills segment $[\underline{\theta}, \theta^H)$ the principal offers a contract asking to produce $q(\theta^H)$ and giving $t(\theta^H)$. This contract is accepted by the agent of this type because it is the better he can choose. So, the problem becomes

$$\mathbf{P3} \quad \max_{q(\theta), \bar{q}} \int_{\theta^H}^{\theta^L} (S(q(\theta)) - \psi(\theta, q(\theta)) - U(\theta)) dF(\theta) \quad (11)$$

$$+ F(\theta^H) [S(q(\theta^H)) - \psi(\theta^H, q(\theta^H)) - U(\theta^H)] - C(\bar{q})$$

$$\underline{\theta} \leq \theta^H \leq \theta^L \leq \bar{\theta} \quad (*)$$

subject to: for $\theta \in [\theta^H, \theta^L]$

$$\theta \in \arg \max_{\tilde{\theta}} t(\tilde{\theta}) - \psi(\theta, q(\tilde{\theta})) \quad (\text{i})$$

$$U = t(\theta) - \psi(\theta, q(\theta)) \geq 0 \quad (\text{ii})$$

$$q(\theta) \leq \bar{q} \quad (\text{iii})$$

In P3 the principal maximizes her expected payoff by choosing the level of investment \bar{q} and by deciding who should be offered the incentive contract determining the values of θ^H , θ^L . The objective function (11) is composed of three terms. The first one (the integral) refers to the expected profit related to intermediate skills segment (as in P2). The second is related to the high skill segment (which we have assumed will choose the contract of the type θ^H). The term related to the low skill types does not appear in the equation because it is nil (the principal offers nothing and pays nothing). Condition (*) indicates that θ^H , θ^L are free to assume the values of the interval $[\underline{\theta}, \bar{\theta}]$. Conditions (i), (ii), (iii) are the same as in problem P2 and are referred exclusively to the intermediate incentivated segment.

Problem P3, after substitution and integration by parts (as in P2 solution), can be restated as follows:

$$\begin{aligned} \mathbf{P3'} \quad & \max_{q(\theta)} \int_{\theta^H}^{\theta^L} \left(S(q(\theta)) - \psi(\theta, q(\theta)) - \frac{F(\theta)}{f(\theta)} \psi_{\theta}(\theta, q(\theta)) \right) f(\theta) d\theta + \\ & + F(\theta^H) \left[S(q(\theta^H)) - \psi(\theta^H, q(\theta^H)) \right] - C(q(\theta^H)) \quad (12) \\ \text{s.t.} \quad & q'(\theta) \leq 0 \quad (13) \end{aligned}$$

This is a problem of calculus of variations with savage term. As in the previous case, we solve the problem as if constraint (a) is not binding and then we check. The solution of P3' can be summarized by equation (14) and (15):

$$S'(q(\theta)) = \psi_q(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{\theta q}(\theta, q(\theta)), \quad \theta^H \leq \theta \leq \theta^L = \bar{\theta} \quad (14)$$

$$S'(q(\theta^H)) - \frac{1}{F(\theta^H)} C'(q(\theta^H)) = \psi_q(\theta^H, q(\theta^H)) \quad (15)$$

Equation (14) is the Euler equation, $\theta^L = \bar{\theta}$ comes from the transversality condition on θ^L and equation (15) is the transversality condition for θ^H . The

Legrende condition ($0 \leq 0$) is respected. Using Dini's theorem we can derive the slope of $q(\theta)$ that is non positive as required by (a):

$$q'(\theta) = \frac{\psi_{q\theta}(\theta, q(\theta)) + \frac{\partial}{\partial \theta} \left[\frac{F(\theta)}{f(\theta)} \right] \psi_{q\theta}(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{q\theta\theta}(\theta, q(\theta))}{S''(q(\theta)) - \psi_{qq}(\theta, q(\theta)) - \frac{F(\theta)}{f(\theta)} \psi_{q\theta q}(\theta, q(\theta))}, \quad \theta^H \leq \theta \leq \bar{\theta} \quad (16)$$

The solution of $P3$ presents some elements of novelty compared with the solutions of $P1$ and $P2$. First, on the left-hand side of equation (14) the term $C'(q(\theta))$ does not appear. This means that the principal after deciding the investment level does not consider in her optimization problem the cost of investment in IT. Second, this cost discounted by a factor greater than one $1/F(\theta^H) \cdot C'(q(\theta^H))$ enters transversality condition (15) that describes the investment decision. Let us rewrit equation (15) as in (17) to obtain an interpretation of $1/F(\theta^H)$.

$$F(\theta^H) \left[S'(q(\theta^H)) - \psi_q(\theta^H, q(\theta^H)) \right] = C'(q(\theta^H)) \quad (17)$$

Consider the marginal expenditure of the principal at θ^H . The principal spends

$C'(q(\theta^H))$ in order to offer an incentive contract to the type $\theta = \theta^H$ and to allow segment $[\underline{\theta}, \theta^H]$ to get the contract of θ^H . The marginal expected revenue (net of the incentive) is given by $\left[S'(q(\theta^H)) - \psi_q(\theta^H, q(\theta^H)) \right]$ times the probability that the agent belongs to $[\underline{\theta}, \theta^H]$. Coeteribus paribus, when investment cost shirks, the segment of high skills types $[\underline{\theta}, \theta^H]$ without incentive contract reduces and θ^H goes closer to $\underline{\theta}$.

Combining equations (5), (9), (14) and (15), we can characterize the solution of $P3$ compared with the solutions of $P1$ and $P2$. Consider first equations (5) and (15) at θ^H . Because the marginal cost of IT is higher in $P3$ than $P1$ (anagously with what was done at the end of the previous paragraph for equations (5) and (9)) the quantity $q(\theta^H)$ in $P3$ is lower than in $P1$. Comparing equation (9) and (14) at θ^H , it is also possible to show (for the same reasoning) that $q(\theta^H)$ in $P3$ is greater than in $P2$. Hence $q(\theta^H)$ in $P3$ is between $q(\theta^H)$ in $P1$ and $P2$. For $\theta^H \leq \theta \leq \bar{\theta}$, using again equations (9) and (14) we get $q(\theta)$ in $P3$ greater than in $P2$. In figure 2, we represent the result in a graph $q(\theta) \times \theta$. The solution to problem $P3$ is differentiated for curve $I3$ (IT investment curve) and curve $Q3$ (use curve). The IT investment curve is constant and parallel to the x-axis. It passes through the intersection of (14) and (15) that we call A. Use curve $Q3$ is flat for the value $\theta^H \leq \theta \leq \bar{\theta}$ and coincides with the investment curve as far as point A, then it slopes down.

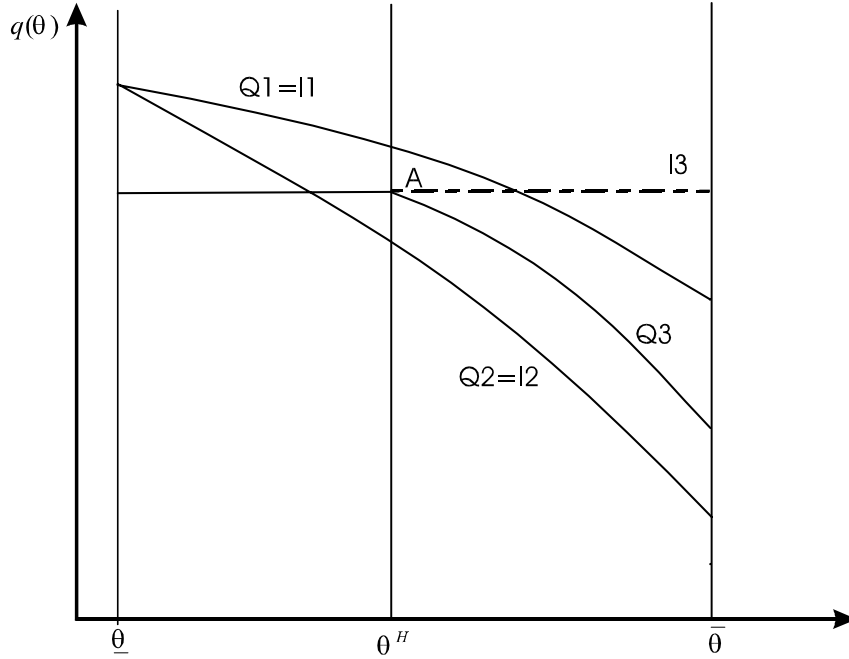


Figure 2: Adoption and use of IT in case of complete information and incomplete information with contractible and noncontractible investment.

5 Discussion

The preceding sections were meant to present the general setting in which we can put our considerations. Standard microeconomic models, which in this paper correspond to the case of complete information or incomplete information with contractible investment predict an optimal or sub-optimal investment. But empirical observation induces us to draw some considerations.

First, we are faced with empirical evidence indicating an over-investment. In fact, it is observed that the marginal return of investment is lower than expected by the standard theory.

Second, recent contributions point out that the employee does not make maximum use of the IT technologies they have.

Third, looking at the trend of these technologies we observe that for the same level of functionality costs have dropped.

Fourth, in many cases firms decide on IT before contracting with employees so the context described in problem *P3* (investment with noncontractible investment) turns out to be the correct one.

On the basis of these observations, we may conclude that:

assuming sufficiently low IT costs and non-contractible investment, incomplete information leads, on average, to over-investment and under-use.

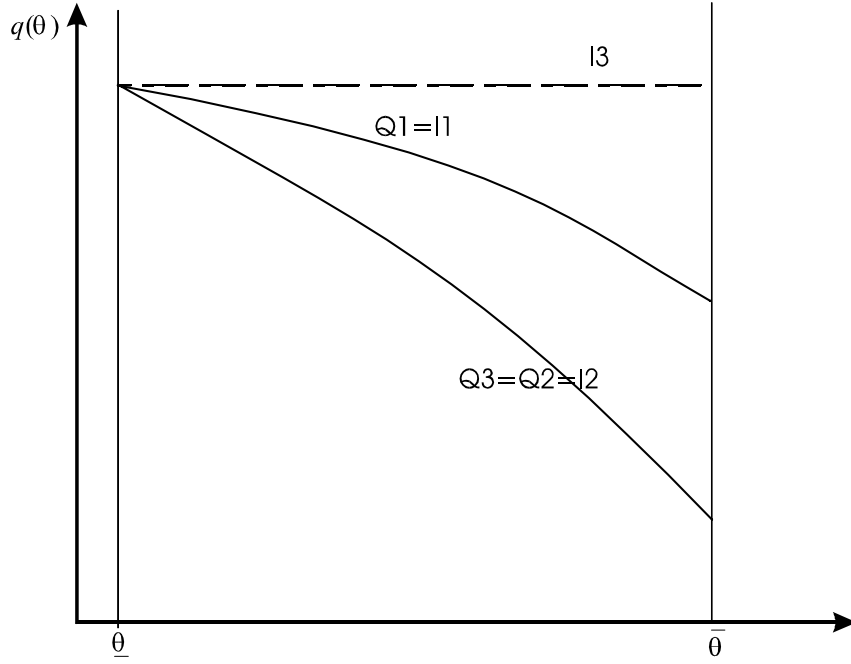


Figure 3: Adoption and use of IT in case of complete information and incomplete information with contractible and noncontractible investment (nil cost).

The sketch of the proof can be done assuming that (marginal) costs tend to zero. We restate (5), (9), (14) and (15) with this assumption:

New solution of $P1$ (complete information):

$$S'(q) = \psi_q(\theta, q) \quad (18)$$

New solution of $P2$ (incomplete information with contractible investment):

$$S'(q(\theta)) = \psi_q(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{q\theta}(\theta, q(\theta)) \quad (19)$$

New solution of $P3$ (incomplete information with noncontractible investment):

$$S'(q(\theta)) = \psi_q(\theta, q(\theta)) + \frac{F(\theta)}{f(\theta)} \psi_{\theta q}(\theta, q(\theta)) \quad (20)$$

$$S'(q(\underline{\theta})) = \psi_q(\underline{\theta}, q(\underline{\theta})) \quad (21)$$

If costs are nil, the main changes are in solution to *P3*: in fact equation (21) describes a situation in which the principal decides to invest in IT for all types of agents, and the IT use (20) coincides with the case of problem *P2* (19). Figure 3 represents the new situation. The level of investment in *P3* is always higher than or equal to the level in *P2* or *P1*, hence there is over-investment. The level of use in *P3* is the same as in *P2* and is always lower than or equal to in *P1*, hence under-use. This result is due to the fact that when investment is noncontractible and its cost is low, the principal does not care to over-invest because her goal is to offer incentive compatible contract to all the types of agents. In any case, it is a context of incomplete information and hence the agent under-uses IT.

6 Conclusions

The paper focuses on modelling the investment and use of IT. It is based on the crucial assumption that investment plays the role of boundary for the maximal level of production. We propose two different cases of imperfect information. The first one (contractible investment) is "standard", the second one is new and helps shed some light on the IT productivity paradox: with IT costs sufficiently low and noncontractible investment, firms, on average, over-invest and under-use IT with respect to the case of complete information. The model presented here does not consider learning-by-doing processes or network externalities, which will have to be investigated in future. Moreover we do not consider multiple-agent situations that might disclose interesting results where system standardization is required.

7 Appendix

The solution to problem *P2* can be derived following Laffont and Tirole [1993]: first, we characterize the transfer scheme that respects the incentive and participation constraint, second we replace it in the objective function so as to obtain an unconstrained optimization problem. The incentive constraint (9.i) requires that agent θ reports his type truthfully. We define $\phi(\theta, \tilde{\theta})$ as the utility of agent θ when he announces $\tilde{\theta}$:

$$\phi(\theta, \tilde{\theta}) \equiv t(\tilde{\theta}) - \psi(\theta, q(\tilde{\theta})), \forall \theta \quad (22)$$

To respect the incentive constraint we require this function to have a maximum at $\theta = \tilde{\theta}$, $\forall \theta$. So, the first order condition is:

$$\phi_{\tilde{\theta}}(\theta, \tilde{\theta}) |_{\theta=\tilde{\theta}} = 0, \forall \theta \quad (23)$$

This means: $t'(\theta) - \psi_q(\theta, q(\theta)) \cdot q'(\theta) = 0, \forall \theta$. It can be shown (see for example Laffont and Tirole [1993]), that when $q'(\theta) \leq 0$, the first-order condition (given by equation (23)) is necessary and sufficient for the optimum.

Let us define $\Phi(\theta) \equiv \phi(\theta, \theta)$ as the indirect utility function of type θ . Differentiating totally (22) (when $\theta = \bar{\theta}$) and substituting (23), we obtain: $\Phi_\theta(\theta) = \phi_{\bar{\theta}}(\theta, \theta) + \phi_\theta(\theta, \theta) = \phi_\theta(\theta, \theta)$. Note that this is an application of envelope theorem to the maximization of (22). This yields

$$\Phi_\theta(\theta) = -\psi_\theta(\theta, q(\theta)) \quad (24)$$

Integrating this expression in $[\theta, \bar{\theta}]$, considering that the participation constraint imposes $\Phi(\bar{\theta}) = 0$, we obtain:

$$\Phi(\theta) = \int_\theta^{\bar{\theta}} \psi_\theta(\theta, q(\theta)) d\theta \quad (25)$$

Hence the transfer, which is the sum of the effort function and utility function is given:

$$t(\theta) = \psi(\theta, q(\theta)) + \int_\theta^{\bar{\theta}} \psi_\theta(\theta, q(\theta)) d\theta \quad (26)$$

The optimization problem may be written as $P2''$:

$$\mathbf{P2''} \quad \max_{q(\theta)} \int_{\underline{\theta}}^{\bar{\theta}} \left[S(q(\theta)) - \psi(\theta, q(\theta)) - \int_\theta^{\bar{\theta}} \psi_\theta(\tau, q(\tau)) d\tau \right] dF(\theta) - C(\bar{q}) \quad (27)$$

$$\bar{q} \leq q(\theta) \quad (\text{iii})$$

$$q'(\theta) \leq 0 \quad (\text{a})$$

Condition (a) is the sufficient condition for the agent's maximization problem of the agent.

Then, integrating by parts the integral and substituting constraint (iii), as for problem $P1$, $\bar{q} = q(\theta)$, we obtain $P2'$.

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