(preliminary; comments welcome)

It Takes Two to Tango: Process Integration and Wages

by

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Abstract

This paper looks at the relationship between technological complexity and wages. Using a panel of UK establishments, we find that wages increase with the degree of complexity, measured both by the task ratio and by the presence of integrated process controls. Our findings are consistent with Kremer's (1993) "O-Ring" production function, which implies strong complementarities among the production activities. The ability to implement performance appraisal systems has a negative and significant effect on wages, consistent with the efficiency wage hypothesis. The use of minicomputers or the existence of a computer network increase the within-firm wage dispersion, which is also consistent with the presence of complementarities in the production process.

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1. Introduction

The last decades have witnessed important changes both in the production structure and in wage dispersion, leading many observers to conclude that new technologies are closely related to rising wage inequality. The most prominent hypothesis is that the introduction of advanced technologies has caused a strong increase in the demand for skilled workers [1]. Further, Kremer and Maskin (1996) have suggested that technological change may have substantially contributed to increasing segregation among workers of different quality into high-wage and low-wage firms. Less attention has been paid to the relation between technological change and increasing within-group wage inequality, or residual variation, mostly attributed to unobserved worker ability [2]. However, according to some recent results by Abowd, Kramarz, and Margolis (1999), individual ability alone cannot entirely explain wage differentials: employer's effects are found to be still relevant. The scope of this paper is to provide a theoretical and empirical analysis, at the *firm-level*[3], of the relation between complex technologies and wage-structure. In particular, our approach can explain why *identical* workers may receive different wages in equilibrium, and why complex technologies may increase wage inequality among workers of different quality.

The first part of the paper develops a theoretical model where technology is represented by the Kremer's (1993) "O-Ring" production function. Production requires the execution of a certain number of risky tasks. The number of tasks is a measure of technological complexity since, if even a single task is mis-performed, output is lost. This notion of technology implies the existence of strong complementarities among the tasks, or activities, that constitute the production process. Similar ideas are put forward also by Milgrom and Roberts (1990, 1995), who argue that the introduction of advanced technologies such as Computer-Aided Design or Computer-Aided Manufacturing (CAD/CAM) systems has increased the degree of interdependence among the productive activities of the firm.

We show that, when monitoring is imperfect, the employer will have an incentive to pay wages that induce employees to elicit a proper level of effort. The adoption of efficiency wages in this context is peculiar to our model. We also show that, when the degree of complexity in production is relatively high, the employer will pay higher wages on average. Furthermore, by considering production processes where different tasks have a different sensitivity to effort, we

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[1] See, among many others, Berman *et al.* (1994), Autor *et al.* (1998), Doms *et al.* (1997), Goldin and Katz (1998), and Haskel and Heden (1999).

[2] On within-group inequality, see for example Gottschalk (1997) and Acemoglu (1999).

[3] The labour-market implications of the basic theoretical model exploited here are explored in Dalmazzo (2000).

show that workers who possess the same ability can be paid different wages depending of the task they are assigned to. Thus, the present model is particularly useful to explain both between-firm and within-firm wage inequality among *identical* workers [4].

The second part of the paper (Section 3) presents some cross-sectional evidence on the relation between technology and wages drawn from WIRS 1990, a survey of British establishments. The aim of our empirical analysis is twofold. First, we seek to assess the impact on wages of proxies for technological complexity, such as use of microprocessor technology, R&D expenditure, and the proportion of complicated tasks. Second, we try to evaluate the impact on the wage structure of measures of inter-dependence in production activities, since the O-Ring model is characterised by complementary tasks.

The results we obtain are consistent with the predictions of the theoretical model. On the one hand, we show that firms that adopt relatively complex technologies pay high wages to *each* category of worker considered (unskilled, semi-skilled, skilled, clerical, supervisor). On the other hand, we show that – differently from most of the literature on computers and wages – not all forms of microprocessor usage are related to higher wages. However, consistently with the notion of the O-Ring technology, we find that the use of integrated process control systems is positively and significantly related to wages. Our analysis has some obvious limits, since we have no measure for the workforce ability. For this reason, we cannot control for "sorting" of high-quality workers into technologically-advanced firms, as the competitive model developed by Kremer and Maskin (1996) suggests. However, our empirical results are consistent with the efficiency-wage hypothesis that forms the basis for our predictions. In fact, we find that the ability to implement performance appraisal systems within the firm – which we interpret as a proxy for the ability to monitor employees – has a negative and significant effect on wages.

The paper is composed as follows. Section 2 develops the basic theoretical model, and extends it to the endogenous choice of monitoring. Section 3 presents the empirical results on the relation between technology, wage levels, and within-firm wage dispersion. Section 4 concludes.

2. The model

In the following section, we develop the basic model of the firm's optimal behaviour when the production function has the O-Ring form and workers can be imperfectly monitored. In section 2.2, we extend the basic model to endogenise the choice of monitoring. In section 2.3, we

[4] On within-firm inequality, see Entorf *et al.* (1999) and the references quoted therein.

examine the effects of product market competition by characterising a zero-profit equilibrium, and obtain the main predictions of the theory.

2.1. The basic framework.

In the model we develop, workers dislike effort and monitoring is imperfect. As in the efficiency-wage model by Summers (1988), we assume that the level of effort e exerted by a worker is given by the following function:

$$e = \begin{cases} \left(\dfrac{w-x}{x}\right)^{\beta} & \text{if} \quad w > x \\ 0 & \text{if} \quad w \le x \end{cases} \tag{1}$$

where w is the wage paid, x denotes the value of worker's labour-market alternatives, and $\beta \in (0,1)$.

For what concerns the firm's technology, we borrow from Kremer (1993) the notion of "O-Ring production function". Production requires that n tasks be correctly performed. Here, the probability that a task is carried out successfully depends on the effort put in by the worker who is in charge of it. Similarly to Kremer and Maskin (1996), production involves a number l of "easy" tasks ($l \le n$), and (n-l) "hard" tasks. We assume that easy and hard tasks have a *different sensitivity to effort*. In particular, an easy task will be performed correctly with probability equal to $q=q(e)$, with $q' > 0$. On the other hand, a hard tasks will be performed correctly with probability $q^z=[q(e)]^z$, where $z>1$. Thus, given the level of effort put in, a hard task is less likely to succeed than an easy task. Without loss of generality, we assume that each task is performed by a single worker.

When: (1) tasks have different difficulty, (2) all the workers assigned to hard tasks put in the same level of effort, and (3) all the workers assigned to easy tasks put in the same level of effort, then the O-Ring production function can be written as follows:

$$y \quad = n \cdot B(n,l;f) \cdot K^{\alpha} \cdot q^{l} \cdot q^{z(n-l)} \tag{2}$$

where K is the firm's capital level, and $B(n,l;f) \cdot K^{\alpha}$ denotes the average per-worker's revenue when *all* the tasks are correctly performed, an event occurring with probability $q^{l} \cdot q^{z(n-l)}$. The variable f denotes the number of identical firms in the industry, and we take $B_f<0$: the higher the number of competing firms, the lower the firm's revenues. Note that the production function (2) entails *complementarity* among tasks: as will be shown, the optimal wage to be paid for a certain task depends on the wage levels paid for all the other tasks, be them easy or hard. This property follows directly from the technology considered: in the most extreme interpretation of Kremer (1993), the degree of integration among tasks is such that, if only one task is mis-performed, the value of production drops to zero.

Although not necessary for our main argument, it can be useful to think of the model as if there were two types of workers: high-skilled (indexed by h) and low-skilled (indexed by l), assuming that workers of different skills cannot be substituted for one another [5]. Then, low-skill workers will be assigned to easy tasks, while high-skill workers will be assigned to hard tasks. For example, managerial tasks will be given only to workers who meet particular requirements in terms of education, experience, etc. When there are common preferences toward labour disutility, equation (1) will hold for both types of workers, with x_h and x_l, denoting respectively the high-skilled and the low-skilled labour-market opportunities. In case that all workers possess the *same* skills, it will hold that $x_h=x_l$.

For simplicity, we take the probability q to be equal to e. Hence, the firm's maximum problem takes the form:

$$\max_{\{w_l,w_h,K\}} \Pi \quad = n\cdot B(n,l;f)\cdot K^{\alpha}\cdot\left(\frac{w_l-x_l}{x_l}\right)^{\beta\cdot l}\cdot\left(\frac{w_h-x_h}{x_h}\right)^{z\beta\cdot(n-l)} - w_l\cdot l - w_h\cdot(n-l) - r\cdot K - F \qquad (3)$$

where $F\geq 0$ represents a fixed cost in production. The firm maximises profit by choosing simultaneously the wage levels w_l and w_h paid to the workers assigned to easy and hard tasks respectively, and the level of capital K.

The solution to problem (3) generates the following set of first-order conditions:

$$\frac{\partial\Pi}{\partial w_l} = \quad \frac{\beta\cdot y}{w_l-x_l}-1 \quad =0 \qquad (4)$$

$$\frac{\partial\Pi}{\partial w_h} = \quad \frac{z\cdot\beta\cdot y}{w_h-x_h}-1 \quad =0 \qquad (5)$$

$$\frac{\partial \Pi}{\partial K} = \quad \frac{\alpha \cdot y}{K} - r \quad = 0 \tag{6}$$

where y is the expected level of production, as defined by (2). Note that the equilibrium wage level w_l depends, through y, on the equilibrium wage level w_h, and *viceversa*. By manipulating the conditions (4) and (5), one obtains that:

$$\frac{w_h - x_h}{w_l - x_l} = z \tag{7}$$

Condition (7) implies that $(w_h\text{-}w_l)>(x_h\text{-}x_l)$. Thus, if the skilled workers' outside opportunities are not worse than the unskilled workers' ones (which is, if $x_h>x_l$), the firm will pay skilled workers a higher wage. The model also captures the particular case when the firm hires workers of the *same* quality to perform tasks of *different* complexity. Then, it holds that $x_h=x_l$, and condition (7) implies that workers assigned to harder tasks will be paid more. Thus, even *within the same firm*, workers of equal skills can be paid different wages. This clarifies that what drives wage dispersion here is not workers' quality, but the fact that different tasks within a firm are differentially sensitive to effort.

We now concentrate on the effects of n and l on the equilibrium values of wages and capital, that is, on w_h , w_l , and K. The number of tasks n can be interpreted as a measure of complexity in production: given l, the greater the number of tasks, the greater the probability that something goes wrong and production is lost. On the other hand, given n, a greater number of *easy* tasks l reduces the weight of hard, and riskier, tasks on the production process.

By differentiating the system (4)-(6), and exploiting the second-order conditions associated with problem (3), one obtains the following:

Result 1. An increase in the number of tasks n will raise the wage paid to high-skilled workers whenever expected revenues are increasing in n: hence, it holds that $dw_h/dn>0$ whenever $dy/dn>0$. Similarly, it holds that $dw_h/dl>0$ whenever $dy/dl>0$.

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[5] By contrast, Kremer and Maskin (1996) consider workers who have intrinsically different productivity and analyze the optimal matching decisions of the firm.

Note also that when dw_h/dn is positive, both dw_l/dn and dK/dn are positive as well, since $(w_h\text{-}x_h)=z\cdot(w_l\text{-}x_l)$ and $K=\alpha(w_h-x_h)/(zr\beta)$. Analogously, when $dw_h/dl>0$, it will hold that $dw_l/dl>0$ and $dK/dl>0$.

These implications of Result 1 need some discussion, because they crucially depend on the sign of dy/dn and dy/dl. What are the plausible signs for dy/dn and dy/dl? Consider first the case of a firm which is considering whether to implement a more complex technology (higher *n*). The technology will be adopted only when profitable, that is, only when the condition $dA/dn>0$ holds. By the envelope theorem, it holds that $dA/dn=dy/dn\text{-}w_h{*}$. Consequently, it must be true that $dy/dn>0$. We can conclude that increasingly complex technologies will only be implemented when revenues *y* are increasing in *n*: this can occur for example when more sophisticated products sell at higher prices. Thus, as implied by Result 1, the adoption of more complex technologies is bound to raise wages.

We can now discuss the effect of a change in *l*. Given the degree of complexity in the technology considered (i.e., given *n*), a rise in *l* implies that some "hard" tasks can be transformed into "easy", less risky tasks. This occurs, for example, when certain tasks requiring a high level of skills can be reduced into "routines" performed by less paid workers[6]. On balance, the net effect of changes in *l* on *y* is intrinsically ambiguous. On the one hand, a greater number of easy tasks, given *n*, reduces the risk and increases revenues' expected value. On the other hand, it is reasonable to expect that the condition $B_l<0$ holds: products that rely on very standardized production methods are likely to sell at lower prices.

As shown in Section 2.3, more precise predictions on the effects of *n* and *l* on wage-levels can be obtained by considering competition among firms.

2.2. Choice of monitoring.

The model developed in the preceding section can be extended to the case when the firm disciplines its workers not only by setting the wage level, but also by choosing the level of monitoring. Higher monitoring intensity facilitates the detection of workers' ill-performance. Two considerations make monitoring relevant. First, monitoring and, more in general, "supervision" has a relevant role in the organization of production (see, among others, Bulow and Summers (1986)). Second, there remains the theoretical possibility that, when the degree of technological complexity increases, firms react by increasing their monitoring intensity *instead of*

6 See the example of the printing industry reported in Mark (1987). See also Bresnahan (1999) on white-collar tasks.

raising wages. We assume that the firm can choose to monitor a worker assigned to a certain task with intensity *m*. The cost of *m* is given by *M(m)*, with $M'>0$ and $M''\geq 0$. Since higher monitoring intensity will induce each worker to exert more effort, we can modify the effort function (1) as follows:

$$e_s = \begin{cases} \left[\left(\dfrac{w_s - x_s}{x_s} \right)^{\sigma} \cdot m_s^{(1-\sigma)} \right]^{\beta} & \text{if } (w_s - x_s, m_s) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where $s=(h,l)$ denotes the worker's type and $\sigma \in (0,1)$.

The maximum problem now takes the following form:

$$\max_{\{w_h, w_l, m_h, m_l, K\}} \Pi \quad = \hat{y} - \left(w_l + M(m_l)\right) \cdot l \; - \; \left(w_h + M(m_h)\right) \cdot (n-l) - r \cdot K - F \tag{9}$$

where

$$\hat{y} \quad = n \cdot B(n,l;f) \cdot K^{\alpha} \cdot \left[\left(\frac{w_l - x_l}{x_l} \right)^{\sigma} \cdot m_l^{(1-\sigma)} \right]^{\beta \cdot l} \cdot \left[\left(\frac{w_h - x_h}{x_h} \right)^{\sigma} \cdot m_h^{(1-\sigma)} \right]^{z \cdot \beta \cdot (n-l)}$$

By calculating and re-arranging the first-order conditions of problem (9), one obtains:

$$\frac{w_s - x_s}{m_s} \quad = \frac{\sigma \cdot M'(m_s)}{(1-\sigma)}, \qquad s = (l,h) \tag{10}$$

Note that, if the degree of convexity of the function *M(m)* is strong, the firm will rely mainly on the wage to induce workers to perform adequately. When the cost of monitoring is linear, that is, when $M(m) = m \cdot \mu$, condition (10) implies that any change that affects the wage-premium $(w_s - x_s)$ will vary the choice of monitoring intensity m_s in the same proportion:

$$\frac{w_s - x_s}{m_s} = \frac{\sigma \cdot \mu}{1-\sigma} \tag{11}$$

The higher the marginal cost of monitoring, μ, the higher is the wage relative to monitoring intensity. Also, when the ability to monitor is rather limited, the employer will pay higher wages.

In conclusion, monitoring does not generally eliminate the need to pay high wages when complex technologies are adopted. For this reason, we will abstract from monitoring in the rest of the theoretical model.

2.3. The effects of competition.

Result 1 holds for a *given* number of firms, *f*. In this section we consider product-market competition through the entry of new firms, in order to obtain sharper predictions from firm-level comparative statics. To this purpose, we impose that the zero-profit condition holds. This condition takes the form [7]:

$$y = w_l \cdot l + w_h \cdot (n - l) + r \cdot K + F \tag{12}$$

Exploiting condition (12) together with equations (4)-(6), one obtains the following system of three equations in (w_l, w_h, K):

$$\beta \left[w_l \cdot l + w_h \cdot (n - l) + r \cdot K + F\right] - (w_l - x_l) = 0 \tag{13}$$

$$z \cdot \beta \left[w_l \cdot l + w_h \cdot (n - l) + r \cdot K + F\right] - (w_h - x_h) = 0 \tag{14}$$

$$\alpha \left[w_l \cdot l + w_h \cdot (n - l) + r \cdot K + F\right] - r \cdot K = 0 \tag{15}$$

By totally differentiating the system (13)-(15) with respect to (w_h, w_l, K, n, l, F), we obtain the following result [8]:

Result 2. *Under the zero-profit equilibrium, it holds that: (i) dw_h/dn, dw_l/dn, and dK/dn are positive, (ii) dw_h/dl, dw_l/dl, and dK/dl are negative, and (iii) dw_h/dF, dw_l/dF, and dK/dF are positive*.

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[7] The zero-profit condition determines *f**, the equilibrium number of firms operating in the market.

[8] The determinant associated to the system (13)-(15) is negative. The proof of Result 2 is rather immediate, although it requires tedious calculations.

Result 2 has some relevant implications. First, when a firm adopts a relatively complex technology (i.e., when n is high in our model), it will be ready to pay relatively high wages to its employees, *be them attached to hard or easy tasks*. Higher complexity raises the risk of failure in production. Thus, since tasks are complementary, the employer will have an incentive to elicit more effort from every employee. In this perspective, wage inequality tends to arise mainly through "plant segregation": there are high-wage plants and low-wage plants according to the type of technology adopted.[9] Many contributions on wages have identified increasing sophistication in technology with the diffusion of computers, and microprocessor technology in general, on the workplace: see Krueger (1993), Berman, Bound, and Griliches (1994), Berman, Bound, and Machin (1998), Dunne, Foster, Haltiwanger, and Troske (2000), among many others. In particular, Autor, Katz and Krueger (1998, p.1168), and Bresnahan (1999) have argued that computers seem to be better suited to eliminate easy tasks, rather than complex and idiosyncratic tasks [10]. In their cross-section analyses on wages, Dunne and Schmitz (1995) and Doms, Dunne and Troske (1997) have used the number of new factory automation technologies to proxy for production process complexity. Van Reenen (1996), and Machin and Van Reenen (1998), among others[11], have elected R&D expenditure as a measure of technological sophistication. Even from our perspective, these measures remain useful to proxy for complexity. However, consistently with the O-Ring approach, we will also need some technological variable to account for the degree of inter-dependence among tasks.

Result 2 has a second important implication for the firm's wage policy, which is related to the proportion between hard and easy tasks. Firms that experiment a decrease in the proportion of easier tasks, as measured by a reduction in l for given level of n, will pay their workers more, *be them attached to hard or easy tasks*. An increase in ratio between hard tasks and easy tasks is what Johnson (1997, p.48) has termed "extensive technological change": our model predicts that this type of technical change will lead the employer to pay higher wages to *all* the employees. Intuitively, an increase in the proportion of hard tasks leads to higher risk of production failure for any given level of effort put in by workers. Consequently, the employer has an incentive to pay higher wages to elicit more effort.

Result 2 has also a third implication. Firms that bear high fixed costs, as measured by F, tend to safeguard their investment by paying high wages, so as to obtain a better performance

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[9] For evidence on plant-segregation, see Davis and Haltiwanger (1991) and, in particular, Kremer and Maskin (1996).

[10] On this issue, see also Johnson (1997).

from their workers. Fixed costs can capture different kinds of sunk investment, such as irreversible equipment, or R&D itself. Moreover, the amount of fixed costs is likely to be related to the firm's size, measured by number of times the basic production process is replicated.

The idea that employer's characteristics, such as the features of technology, drive the firm's wage-policy has been widely discussed. As argued by Krueger and Summers (1987,1988), technological factors seem to be very relevant to explain wage structures over different countries. Moreover, Katz (1986) and Gibbons and Katz (1992) have noted that inter-industry wage "relativities" are remarkably similar in different occupations. On the basis of Katz's evidence, Layard, Nickell, and Jackman (1991, p.167) have concluded that "this is not at all consistent with a technological approach. Why should the responsibilities of office workers, janitors, technicians, and operatives in different industries all vary in proportion? It seems most unlikely."[12] However, the objection raised by Layard *et al.* (1991) is not valid when technology is represented by an O-Ring production function. In the O-Ring perspective, production succeeds when a number of inter-dependent operations are performed correctly. Consequently, ill-performance by an electrician in the production of airplanes can have more dramatic consequences that his sloppy performance in the car industry.

The use of the O-Ring production function is consistent with alternative wage theories. According to the efficiency-wage approach we follow, complicated technologies induce firms to pay high wages, so as to improve performance. By contrast, the competitive approach followed by Kremer and Maskin (1996) predicts that firms adopting complex technologies will hire high-skill, high-wage workers. Hence, increasingly complex technologies may lead to skill-segregation among plants [13]. Note however that, if skills were the only relevant factor and monitoring problems were irrelevant, the presence of incentive schemes would be difficult to explain.

Another implication of the model is related to the wage gap between workers performing hard tasks and workers performing easy tasks. The following result holds:[14]

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[11] See also Berman *et al*. (1994).

[12] A similar point is made in Gibbons and Katz (1992).

[13] The model in Kremer and Maskin (1996) is consistent with explanations based on "skill-biased technical change" and, more in general, with the idea of skill-technology complementarity: see Goldin and Katz (1998).

[14] To verify Result 3, note that $d(w_h - w_l)/dn = z\ (dw_h/dn)$.

Result 3. *An increase in n, or a decrease in l, will raise the wage differential between* w_h *and* w_l.

This Result has interesting implications for the wage policy followed *within a firm*, and in particular for what concerns within-firm inequality. Increasing within-firm wage inequality has been observed by Davis and Haltiwanger (1991) in US manufacturing plants, and by Kramarz, Lollivier and Pelè (1996) for France. According to Entorf, Gollac, and Kramarz (1999), this phenomenon is accounted for – at least in part – by the introduction of new technologies.

To summarize, the simple model presented may account for two types of wage inequality:

(i) *Within-Group wage inequality*. Our model can explain why identical workers can be paid different wages in equilibrium. Suppose that all workers possess homogeneous skills. According to Result 2, firms that adopt complex technologies will pay their workers higher wages than firms that use simple technologies (*within-group, between-plant inequality*). Furthermore, Result 3 predicts that identical workers can be paid different wages by the same employer depending on the task they are assigned to (*within-group, within-firm inequality*).

The stylised assumption that all workers possess the same skills is patently extreme, but it neatly shows the peculiar implications of our model with respect to others. Our model can fully account for within-group wage dispersion, since it depends on employer's effects related to technology. By contrast, competitive models treat residual variation merely as unobserved ability.

At the same time, it is quite reasonable to suppose that hard tasks are likely to be given to high-quality workers. Under this presumption, our results can explain wage inequality among heterogeneous workers:

(ii) *Between-Group wage inequality*. Firms that adopt riskier technologies – as measured by a higher n, or a lower l – will exhibit greater wage dispersion (see Result 3). Consequently, the more complex the technology, the greater the level of wage inequality among high-skill and low-skill employees.

3. Empirical analysis

The theoretical implications of the model are tested in what follows. Section 3.1 presents the empirical strategy. Section 3.2 describes the data we use. Finally, Section 3.3 presents and discusses the empirical findings.

3.1. An empirical model

The theoretical model set out in section 2 has important empirical implications. Both the level and the distribution of wages in the firm are related to the complexity of the production process. Result 2 implies that the wages of *all* categories of workers should be positively affected by the relative proportion of complex tasks in production. Result 3 predicts that the variability of wages at the firm level should be an increasing function of the relative proportion of complex task.

Let **x** denote a vector of controls for wages and u^j , j=1, 2, 3, denote a stochastic disturbance. We can write the following empirical relationships:

$$\overline{w} = f^1(n/l, \mathbf{x}, u^1) \tag{16}$$

$$w_s = f^2(n/l, \mathbf{x}, u^2) \qquad s = h,\ l \tag{17}$$

$$\sigma_w^2 = f^3(n/l, \mathbf{x}, u^3) \tag{18}$$

Equation (16) says that the average wage in the firm ($\overline{w}$) is a stochastic function of the ratio of complex tasks, *n/l*, and of a vector of control variables, **x**. According to Result 2, the average wage is an increasing function of the task ratio: $\partial\overline{w}/\partial(n/l) > 0$. Equation (17) says that, *ceteris paribus*, the wage of every category of workers is an increasing function of the task ratio: $\partial w_s/\partial(n/l) > 0$, *s*=*h, l*. Both equations (16) and (17) are implied by Result 2. Equation (18) says that, after controlling for the other factors affecting wages, the variance of wages at the firm level, σ_w^2, is an increasing function of the complexity of production as proxied by the task ratio: $\partial\sigma_w^2/\partial(n/l) > 0$. Equation (18) is implied by Result 3, which says that the wage differential between high- and low-complexity jobs is an increasing function of the ratio of high- to low-complexity tasks in the firm.

Apart from the variables that capture the role of complexity or process integration, equations (16)-(18) should include the following main categories of regressors: technological variables and labour/union variables. The technological variables can capture the productivity differences across firms that are not related to the task ratio. The labour and union variables could capture both the firm's ability to monitor its employees and the relative bargaining power of workers in wage setting. In addition, we can include industry dummies to control for all the other differences across industries for which we do not have explicit information.

3.2. The data

The data set consists of a sample of 284 UK establishments from the 1990 Workplace Industrial Relations Survey (WIRS). This data set is particularly attractive since it contains information on a number of technological and union variables at the establishment level. In addition, WIRS provides information on financial variables and on product market characteristics. We limit our sample to establishments operating in the trading sector: governmental organisations and non-trading public corporations are therefore excluded from our analysis.

The data we use in our analysis are summarised in Table 1. The dependent variables are the median wages of unskilled, semi-skilled, skilled, clerical and supervisor employees. We also construct the average hourly wage as the weighted average of the above wages by category of workers. Our measure of wage dispersion is the sum of the proportions of employees earning less than half the average wage or more than twice the average wage in the establishment.

The main variable measuring the complexity in production is the task ratio, defined as the proportion of middle/senior managers and senior technical/professionals on total employment. This can be seen as capturing the proportion of hard tasks over total tasks. The theory predicts a positive effect on all wages, including the wages paid by the firm to the workers who perform easy tasks.

Another critical variable is the presence of integrated process controls (*IPC*). This is defined as the microelectronic control of integrated processes, where the control involves several stages of production processes. This variable measures the intensity of the interdependency across tasks. A higher degree of integration exacerbates the consequences on total production of mistakes in a single task. The effect on wages should be positive for all categories of workers.

We also include two variables related to computer usage: the presence of minicomputers and the existence of a computer network. The first variable can be seen as mainly capturing the complexity of tasks in the establishment, and the second variable as mainly capturing the degree of interdependency across tasks. Both variables measure the use of advanced technology and complementarity among production tasks. The proportion of total expenditure of the organisation spent on R&D can also be seen as a measure of the complexity of tasks in production.

Among the technological variables, we include measures of relative productivity. These measures consist of a comparison of labour productivity in the establishment with other similar workplaces. Another important technological variable is the size of the establishment, which we measure by total employment. The size of the establishment is also important for: (1) the ability of the firm to monitor its employees: the bigger the size, the more difficult it is to monitor workers (the expected sign on wages is therefore positive); (2) a measure of fixed costs: larger firms tend to be associated with larger fixed costs (the model again predicts a positive effect).

Among the labour variables, union effects are measured by the proportion of unionised employees on total employment. This variable can influence the outcome of bargaining over the wage above the efficiency wage level (which would then place a lower boundary on the range of wages). We expect a positive sign. We also consider the existence of performance appraisal systems, *i.e.* individually written assessments produced periodically by managers or supervisors. Appraisal systems are likely to be associated with higher monitoring ability. It is therefore possible to elicit a given level of effort with a lower level of wages. The sign predicted by the theory is therefore negative. An additional labour control is turnover: a higher turnover could lead to higher efficiency wages being paid.

We include one-digit industry dummies in our regressions to capture any inter-industry source of differences in wages. Our regressions therefore capture the intra-industry structure of wage levels. Additional controls in our empirical regressions were measures of output demand elasticity, product characteristics, foreign ownership, market structure indicators, entry barriers, financial performance, joint consultative committees, capacity utilisation, and usage of special tools and machinery.

3.3. Empirical findings

Table 2 presents regressions of the average hourly wage. Column (1) includes establishment size (*SIZE*), the unionisation rate (*UNION*), the existence of appraisal systems (*APPRAISAL*), the task ratio (*TASK RATIO*), the presence of integrated process controls (*IPC*), and the interaction between the task ratio and integrated process control. All variables are significant and have the expected sign. Size, which may capture both the ability to monitor and fixed costs, has a positive effect on the average wage, as expected. The unionisation rate has a positive effect on the average wage. The ability to monitor measured by the existence of an appraisal system reduces the average wage by about 11%. The most important variable for us is the presence of integrated process controls. Their marginal effect is positive and estimated at 0.09 at the sample average. On average, thus, the presence of integrated process controls increases the average wage by about 9%.

Column (2) also includes expenditure on R&D, both on its own and interacted with the task ratio. The marginal contribution of R&D is positive when estimated at sample average, but not statistically significant. The coefficients on the other variables are not affected by the inclusion of R&D.

Column (3) and (4) include additional controls: these are whether the productivity in the establishment is higher or lower when compared with similar workplaces, and the turnover ratio. The productivity variables have the correct sign, but they are not statistically significant, both without and with R&D. A higher turnover is associated with a lower average wage, but again the regressor is not statistically significant.

We have also included a number of alternative regressors, but they are not statistically significant. In particular, in contrast to other empirical studies (Krueger, 1993; Autor, Katz and Krueger, 1998; DiNardo and Pischke, 1997) which find that computer use has a positive influence on wages, we find that various measures of the adoption of computing facilities have no significant effect on the level of wages, once we control for integrated processes.

Doms, Dunne and Troske (1997), Dunne, Foster, Haltiwanger and Troske (2000) use measures of technological advancement at plant level (such as CAM/CAD) and find a positive association with wages. Among the alternative measures of microelectronics applications that we use (such as design, control of individual machines, control of individual items of processed plants, centralised machine control of groups of machines, IPC, automatic handling of products and materials, etc.), by far the most important one is IPC. We also find that the use of alternative types of tools and machinery have no significant effects on wages.

We should note that we cannot control for the ability or skill of workers, but industry dummies can partly capture the sorting of skills among production sectors (Bartel and Sicherman, 1999).

Table 3 presents the estimates corresponding to column (2) of Table 2 for the median wages of individual categories of workers: unskilled, semi-skilled, skilled, clerical and supervisors. The task ratio, integrated process control and their interaction remain significant for all groups of workers. An important result is that the estimated coefficients for the task ratio tend to increase with the degree of worker specialisation. The unionisation rate and the appraisal system are both quantitatively more important and more statistically significant for manual workers (unskilled, semi-skilled and skilled). A possible explanation for the latter finding is that the ability to monitor through the appraisal system decreases with the relative complexity of the task. R&D tends to be quantitatively more important for clerical and supervisors, although it is not statistically significant.

Table 4 presents regressions on the wage dispersion at establishment level *(within-firm wage dispersion*). The dependent variable is the sum of the proportion of employees whose wage is greater than twice the average wage in the establishment, or less than half the average wage. The dependent variable is therefore a measure of the variability of the distribution of wages in the establishment. Column (1) shows that size has a negative influence on wage dispersion. Combining this result with tables 2 and 3, we can infer that, on average, larger firms pay higher wages and display lower within-firm wage variability. Unionisation has a negative influence on wages, consistent with what we would expect on the role of union. Following our theoretical discussion in section 2, the microelectronics variables we consider are the use of minicomputers, the existence of a computer network, and the task ratio. Minicomputers have a positive effect, consistent with greater complexity. The presence of a computer network has a positive effect, consistent with enhanced interdependency across tasks. The task ratio has a positive influence, as we would expect from the theory, although its effect is not statistically significant.

Columns (2) and (3) present parsimonious representations of column (1). The effects of the variables are confirmed when we only include minicomputers or the existence of a computer network.

To summarise the results in Table 4, although our data do not confirm a direct effect of microelectronics on the level of wages (unlike, for instance, Krueger, 1993, and Entorf, Gollac and Kramarz, 1999), we do find that the presence of a computer network or the use of mini-computers tends to increase the *within-firm* dispersion of wages. Both a computer network and a mini-computer can be seen as associated with a greater degree of inter-dependency among the tasks carried out by individual workers. Our findings are therefore consistent with the view that the within-firm wage differential increases with the relative complexity of tasks in the firm.

4. Concluding remarks

This paper looks at the relationship between technological complexity and wages. Using a panel of UK establishments, we find that wages increase with the degree of complexity, measured both by the task ratio and by the presence of integrated process controls. This is true both for the average wage in the establishment, and for the wage of each category of workers. Our findings are consistent with Kremer's (1993) "O-Ring" production function, which assumes strong complementarities among the production activities. We also find that the ability to implement performance appraisal systems has a negative and significant effect on wages, consistent with the efficiency wage hypothesis. The use of minicomputers or the existence of a computer network increases the within-firm wage dispersion, consistent with the presence of complementarities in the production process.

We do not have information on individual workers' quality at the firm level, and cannot therefore rule out that more complex tasks are associated with higher wages because of their complementarity with skills (Goldin and Katz, 1996, 1998). Our findings however show that the task ratio exerts a positive influence on the wages of *all* categories of workers, and are therefore consistent with the existence of strong complementarities among tasks, as suggested by the "O-Ring" technology.

List of variables

The expressions in brackets denote the WIRS (1990) code.

Total employment; number of employees by category. (C1).
Median pay. (K12).
Hours per week. (K13).
Paid overtime hours. (K14).
Proportion of full-time employees earning half the average gross earnings or less. (K15).
Proportion of full-time employees earning twice the average gross earnings or more. (K16).
Number of employees who resigned during the last twelve months. (P1).
Presence of integrated process control. (A26_07).
Mini-computers use. (A27_03).
Presence of a computer network. (A27_05).
Proportion of organisation's total current expenditure spent on research and development. (FB13).

Table 1. Descriptive statistics

	mean	*standard deviation*	*median*	*25% percentile*	*75% percentile*
Log average hourly wage	1.4387	0.3424	1.4788	1.3001	1.6337
Log average hourly wage, unskilled	1.2403	0.3499	1.2909	1.0878	1.4424
Log average hourly wage, semi-skilled	1.3888	0.3329	1.4307	1.2648	1.5784
Log average hourly wage, skilled	1.5774	0.3403	1.5988	1.4397	1.7636
Log average hourly wage, clerical	1.3858	0.3753	1.4171	1.2809	1.5523
Log average hourly wage, supervisor	1.6986	0.3948	1.7504	1.5506	1.9185
Wage dispersion	16.0166	21.6360	2	6	17
Number of employees	995.8	1086.1	680.0	295.0	1329.5
Union recognition	0.6292	0.3487	0.7578	0.3656	0.9237
Performance appraisal system	0.3415	0.4751	0	0	1
Task ratio	0.1107	0.0960	0.0800	0.0489	0.1340
Integrated process control	0.3415	0.4751	0	0	1
Mini-computers	0.7739	0.4191	1	1	1
Computer network	0.6678	0.4718	0	1	1
Research and development	0.9401	3.0434	0	0	0
High productivity	0.1585	0.3658	0	0	0
Low productivity	0.0845	0.2786	0	0	0
Turnover	0.1096	0.1532	0.0627	0.0250	0.1268

Table 2. Process integration and average wage.

Dependent variable: log average hourly wage	(1)	(2)	(3)	(4)
SIZE	0.0000319** (0.000015)	0.0000284* (0.0000149)	0.0000489** (0.0000165)	0.0000431** (0.000016)
UNION	0.1580383** (0.0662283)	0.1679017** (0.0663437)	0.1412997** (0.060107)	0.1567733** (0.059357)
APPRAISAL	-0.1103196** (0.05121)	-0.1000636** (0.0514322)	-0.0628487 (0.042037)	-0.051811 (0.042557)
TASK RATIO	0.8425846** (0.217261)	1.030174** (0.262627)	0.6320191** (0.196729)	0.8303971** (0.242461)
IPC	0.2151123** (0.073513)	0.2021293** (0.069097)	0.1728162** (0.067289)	0.1596943** (0.062451)
TASK RATIO *IPC	-1.00562** (0.47769)	-0.971915** (0.4006979)	-0.9316319* (0.49545)	-0.8836626** (0.402477)
R&D	—	0.0236804 (0.019477)	—	0.0205348 (0.01938)
TASK RATIO *R&D	—	-0.15345 (0.114127)	—	-0.1433107 (0.113673)
HIGH PROD	—	—	0.0120027 (0.048266)	0.0062748 (0.0486694)
LOW PROD	—	—	-0.05602 (0.071753)	-0.060321 (0.075306)
TURNOVER	—	—	-0.1544502 (0.183456)	-0.140041 (0.184975)
Industry dummies	Yes	Yes	Yes	Yes
n	284	284	270	270
F_1	5.35**	4.07**	3.30**	2.77**
F_2	4.76**	4.73**	4.62**	4.64**
R^2	0.1987	0.2116	0.2169	0.2317
se	0.3138	0.31243	0.28863	0.28702

Notes:
Heteroscedasticity-consistent *s.e.* in brackets.
*: statistically significant at 10% level; **: statistically significant at 5% level.
F_1: joint significance of explanatory variables.
F_2: joint significance of industry dummies.

Table 3. Process integration and wages by category of workers.

Dependent variable: log average hourly wage	*Unskilled*	*Semi-skilled*	*Skilled*	*Clerical*	*Supervisors*
SIZE	0.000045**	0.0000237	0.0000224	0.0000445**	0.0000304*
	(0.000016)	(0.0000146)	(0.0000153)	(0.000017)	(0.000017)
UNION	0.175254**	0.1968196**	0.1905938**	0.0738355	0.1158761
	(0.070732)	(0.06957)	(0.06636)	(0.075706)	(0.083462)
APPRAISAL	-0.1232139**	-0.117116**	-0.092907*	-0.0292428	-0.0602387
	(0.050332)	(0.049117)	(0.050324)	(0.054534)	(0.05435)
TASK RATIO	0.6279454**	0.7563357**	0.9561889**	0.9219136**	1.03209**
	(0.26427)	(0.267502)	(0.28588)	(0.280989)	(0.312482)
IPC	0.1791657**	0.247069**	0.2281434**	0.1912421**	0.2408877**
	(0.074794)	(0.061919)	(0.065869)	(0.074501)	(0.076483)
TASK RATIO *IPC	-0.8040623*	-1.129559**	-1.074697**	-1.103659**	-1.08822**
	(0.412708)	(0.403450)	(0.411807)	(0.428232)	(0.4698)
R&D	0.0056168	0.0161337	0.0088467	0.021795	0.0203728
	(0.020000)	(0.021374)	(0.02067)	(0.021902)	(0.020942)
TASK RATIO *R&D	-0.0630803	-0.1105014	-0.1162685	-0.1590408	-0.1355007
	(0.108268)	(0.116641)	(0.120641)	(0.121301)	(0.113962)
Industry dummies	Yes	Yes	Yes	Yes	Yes
n	284	284	284	284	284
F_1	4.85**	5.41**	4.92**	3.11**	2.98**
F_2	5.23**	3.78**	2.36**	4.50**	4.92**
R^2	0.1979	0.2071	0.1638	0.1648	0.1667
se	0.32206	0.30458	0.31974	0.35248	0.37033

Notes:
Heteroscedasticity-consistent *s.e.* in brackets.
*: statistically significant at 10% level; **: statistically significant at 5% level.
F_1: joint significance of explanatory variables.
F_2: joint significance of industry dummies.

Table 4. Wage dispersion.

Dependent variable: Wage dispersion	(1)	(2)	(3)
SIZE	-0.00360**	-0.00291**	-0.00327**
	(0.00110)	(0.00108)	(0.00108)
UNION	-12.728**	-13.430**	-13.162**
	(5.035)	(5.071)	(4.957)
TASK RATIO	48.167	33.203	34.273
	(39.217)	(22.545)	(35.029)
MINICOMPUTERS	6.078*	8.196**	—
	(3.693)	(3.422)	
TASK RATIO * MINICOMPUTERS	-24.506	-29.437	—
	(24.481)	(24.694)	
NETWORK	8.556*	—	9.864**
	(4.706)		(4.393)
TASK RATIO * NETWORK	-25.477	—	-30.743
	(37.043)		(36.343)
Industry dummies	Yes	Yes	Yes
n	240	240	240
F_1	5.28**	5.48**	5.66**
F_2	2.27*	2.03	2.19*
R^2	0.1788	0.1628	0.1729
se	20.248	20.354	20.231

Notes:
Heteroscedasticity-consistent *s.e.* in brackets.
*: statistically significant at 10% level; **: statistically significant at 5% level.
F_1: joint significance of explanatory variables.
F_2: joint significance of industry dummies.

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