What happens when agent *T* gets a computer?

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Contents

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Abstract

During the last decade a great many authors have shown that computers have a large impact on skill demand, production processes, and the organization and intensity of work. Analyses have indicated that the rates of change of these variables have been the largest in the more computer-intensive sectors. Empirical findings, however, suggest that the effects of computers on the labor market are complicated and difficult to trace. This paper offers a simple model to explain how computers have changed the labor market. The model demonstrates that wage differentials between computer users and other workers are consistent with the observation that computers are first introduced in high-wage jobs because of cost efficiency. It also shows that neither computer skills nor complementary skills are needed to explain skill upgrading, changes in product characteristics, and the organization and intensity of work. Finally, it is shown that these findings shed a different light on the way computers have changed the labor market and on the changes to be expected following the further diffusion of computers.

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1 Introduction

The introduction of computers has substantially changed the labor market in recent years. An analysis of the Current Population Surveys shows that in the United States computer use at work has more than doubled from a mere 24.3 percent in 1984 to 52.5 percent in 1997. This use is not evenly distributed among workers: in 1997, 74.9 percent of the workers with a college degree used a computer, while only 38.6 percent of the high-school graduates employed a computer on the job. It is also observed that the average wages of computer users are substantially higher than that of non-users. Even after controlling for personal characteristics, educational background, occupation and sector of industry, a computer wage premium of 17.2 percent was found for the United States in 1984, which slightly increased from the early 1980s to the early 1990s (e.g. Krueger, 1993, and Autor, Katz and Krueger, 1997).[1] In addition, both firm-specific case studies[2] and economy-wide investigations[3] reported a positive correlation between skill upgrading of the workforce and computer use.[4] Skill upgrading is typically observed within industries and there is no evidence for employment shifts towards industries with high rates of computer utilization.[5] Finally, the introduction of computers at the workplace is typically associated with changes in the organization of the production process, new human resource practices, modifications of product specifications, and changes in product characteristics[6] and seems to be positively correlated with work intensification[7],

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[1] Computer wage premiums are obtained from an ordinary least squares regression with the log of the hourly wage as the dependent variable and computer use and other covariates as independent variables (e.g. Krueger, 1993). Our own calculations show that between 1993 and 1997, the computer wage premium fell slightly to 15.7 percent. Similar observations apply to other OECD countries (see Borghans and Ter Weel, 2000b, for an overview).

[2] E.g., Groot and De Grip (1991), Levy and Murnane (1996), Autor, Levy and Murnane (2000) and Fernandez (2001).

[3] E.g., Bound and Johnson (1992), Berman, Bound and Griliches (1994), Dunne and Schmitz (1995), Chennells and Van Reenen (1997), Doms, Dunne and Troske (1997), Entorf and Kramarz (1997), Autor, Katz and Krueger (1998), Berman, Bound and Machin (1998), Machin and Van Reenen (1998), Katz and Autor (1999), Dunne, Foster, Haltiwanger and Troske (2000) and Bresnahan, Brynjolfsson and Hitt (2001).

[4] Autor, Katz and Krueger (1998) report that the growth of the mean computer investment share from .026 in the 1970s to .057 in the 1980s can account for a rise of about 36 percent in the rate of within-industry skill upgrading from the 1970s to the 1980s in U.S. manufacturing.

[5] Using the Autor, Katz and Krueger (1998) data we do not find that industries using and investing more in advanced technologies are expanding relative to other industries.

[6] E.g., Berndt and Morisson (1995), Bresnahan, Brynjolfsson and Hitt (1999), Cappelli and Carter (2000), Caroli and Van Reenen (2000), Lindbeck and Snower (2000) and Autor, Levy and Murnane (2001).

[7] E.g., Lindstroem (1991), Carayon-Sainfort (1992) and Green and McIntosh (2000).

other ways in which workers cooperate and produce within a firm (Kremer and Maskin, 1997 and Acemoglu, 1999) and increased firm size (Barras, 1990).[8]

The shift in labor demand towards skilled workers has particular appeal to the idea that computers are a major source of skill-biased technical change. The most common explanation is that on-the-job computer use requires specific skills.[9] The basic findings seem to fit in well with the argument that workers possessing such skills earn higher wages and are allocated to jobs in which computers are used. Apparently these skills are particularly present among skilled workers, which explains the differences in computer use between relatively skilled and unskilled workers. Unobserved differences in skill requirements for computer use are reflected in a computer wage premium and the increased demand for skilled workers following the introduction of the computer seems to confirm

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[8] Barras (1990) argues that computerization reduces transaction costs of information flows within a firm, increases the efficiency of use of resources and improves the returns to the management function, all of them leading to expansion of the firm.

[9] As argued by Katz (2000), there is no *a priori* reason why the introduction of computers only affects the position of workers who actually work with a PC or computer terminal. For that reason computer use can be regarded as a crude proxy for technological change. Empirical evidence shows, however, that computer use is actually correlated with a large number of labor market aspects. In this paper we therefore investigate primarily what happens to computer users, to improve our understanding of these findings.

that higher-skilled workers are needed to operate a computer. Apart from computer skills themselves (e.g., Krueger, 1993, Hamilton, 1997, Miller and Mulvey, 1997 and Green, 1999), various studies also discuss complementary skills, by which some workers benefit more from the possibilities of computers than workers who do not possess these skills (e.g. Levy and Murnane, 1996, Bresnahan, 1999 and Autor, Levy and Murnane, 2001).

Empirical analysis of these two hypotheses concerning the role of computers raises doubts about the interpretation of how computers have changed the labor market. For example, (i) a large computer wage premium goes to such computer tasks as emailing and word processing (Krueger, 1993); furthermore, rather than electronic or mechanical cash registers, the use of computerized cash registers is associated with a wage premium (Green, 1999), (ii) DiNardo and Pischke (1996) show that it is by no means true that all those who embody computer skills are working in jobs in which computers are used; a fairly large number of people work in jobs in which computers are used even though they have no computer skills, (iii) for most cases of computer use there appears to be no relationship between wages and computer skills (Bell, 1996 and Borghans and Ter Weel, 2000a), (iv) companies employing advanced technologies, such as computers, seem to pay their employees on average higher wages regardless of whether these employees use these new technologies (Doms, Dunne and Troske, 1997), and (v) based on job analyses it can be concluded that at all skill levels jobs and tasks are found that seem to be well suited to computerization (Autor, Levy and Murnane, 2001); while higher-skilled workers use a computer more frequently, a substantial fraction of lower-skilled workers employs a computer as well (Bresnahan, 1999).

These results seem to illustrate that the way in which computers affect the labor market is highly complicated and notoriously difficult to trace. This is hardly surprising given that, apart from a worker's productivity and required educational level, computers change the specifications of the products produced, the price of the product on the goods market, and the way in which cooperation and collaboration with fellow workers is established. All of these aspects influence the demand for different types of labor and products simultaneously. Due to the wide diffusion of computers, these changes are likely to influence the wage structure, which in turn influences the demand for and supply of skills. Furthermore, it is difficult to obtain a clear empirical picture of the genuine effects of computer use on the changing skill demand, the modifications of the production process and the organization and intensity of work because computer users differ from non-users with respect to a great many observed and unobserved characteristics.

More insight into the impact of computers on the labor market could be gained by an experimental approach in which a computer is made available to a randomly drawn group T of treated workers, while a control group U (untreated people) does not get one. An advantage of this approach is that random assignment excludes selection effects and only addresses the effects of the computer at work. Because of the small scale of this experiment, market effects due to changes in product prices and market wages are negligible.[10] The main problem of such an experimental approach is that it is not clear what kind of computer facilities group *T* should be provided with, because the usefulness of the facilities depends heavily on the tasks to be performed, the configuration of the computer, the particular software available and installed, and the information databases available for use. Furthermore, settings between different jobs will vary to a large extent and it seems to be impossible to guarantee an acceptable experiment.[11] In addition, the possibility to use a computer requires users to recognize its options. The practice that the introduction of a computer is preceded by a detailed investigation of the wishes of both firms and workers can seldom be simulated in such an experiment.

As an alternative route to investigate the impact of computers on the labor market, this paper proposes a simple model analyzing what would happen in such an experiment. As a main feature, the model considers two identical workers who have similar jobs consisting of two tasks, one of which can be computerized, while the other cannot. We investigate what will happen if we assign a computer to agent *T* and not to agent *U*. Because we deal with artificial agents rather than with real workers, we are able to abstract from differences between workers. This enables us to investigate the different effects of the introduction of the computer separately and rule out the effects of unobserved heterogeneity. Most importantly, this approach enables us to compare the impact on two identical people in a situation where one is provided with a computer and the other is not. Similarly, it also allows for comparison of the effects of computer use between two workers that differ only in one specified aspect of their job. Although our primary focus is on the impact of computers in the workplace, we also derive market effects resulting from the introduction of computers by aggregating the results.

Based on the insights into how work changes following the introduction of a computer, we try to find out when a firm decides to introduce a computer in a particular job and derive the effects on wages, skill requirements, product characteristics, and the organization and intensity of work. We show that the empirical findings presented above fit into our model in a rather straightforward manner. In particular, we show that, given the tasks of a worker, high wages themselves are an important factor in explaining the introduction of computers because the relative costs for high-wage

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[10] DiNardo and Pischke (1997) put forward a case in favor of such an experiment.

[11] For example, what is the point of assigning a computer to a lumberjack or taxi cab driver and measuring the labor market impact? Such an exercise would be about as meaningful as randomly assigning a chainsaw to an economist to do his job.

workers to carry out a task are much higher than for low-wage workers accomplishing the same task. Hence, a firm gains more by letting a high-wage worker bring this task to completion using a computer. In this way we obtain that neither computer skills nor complementary skills are needed to explain wage differentials between computer users and others. Even random wage differentials between equal workers lead to differences in computer use. These findings shed a different light on the way computers have changed the labor market and on the changes to be expected following the further diffusion of computers at the workplace. Although the introduction of computers might induce skill upgrading and affect wages, we show that wage differentials are not likely to increase further as computer use increases. On the other hand, if computers will have become sufficiently cheap, unskilled workers will also face increased computer use and experience similar wage and skills requirement increases.

The plan of the paper is as follows. In Section 2 we start with the basic set-up of the model, in which we investigate jobs with multiple tasks. In Section 3 we introduce agent U and T and discuss what happens when agent T is provided with a computer. In Section 4 we discuss the effects of the introduction of the computer on the product market and labor demand, we interpret the value of skills and the way a computer changes the optimal skill level and product characteristics. In Section 5 we present some extensions to the model to show how computerization might influence the firm as a whole, the way people cooperate within a firm and work intensity. Section 6 concludes.

2 A model of jobs with multiple tasks

Consider an agent with skills s, where $s = (s_1, s_2, ..., s_n)$ might be either a uni- or multi-dimensional parameter describing the skills of this agent. The n components of the vector s are the agent's characteristics determining the ability to perform a certain task. Years of education will typically be one component of the vector s, but also more specific characteristics such as mathematical skills or social abilities and experience are included in this vector. The agent produces a good with characteristics p.

To perform his job, agent i has to fulfil two tasks: task 1 and task 2. For simplicity, we assume that task 1 generally represents aspects of a job that could in theory be computerized. Furthermore, we assume that task 2 is one that cannot be computerized.[12] These tasks represent two independent aspects of a job that are nevertheless undeniably interrelated and very hard to separate.[13]

Based on arguments of comparative advantage, it is usually assumed that every worker performs only those tasks in which his relative productivity is highest. Occupational descriptions like DOT and O*NET, however, show that in practice occupations tend to include several tasks, which clearly require entirely different types and levels of skills. The reason why it would be costly to separate the two job aspects in question is related to transaction costs: if two tasks are part of one job but carried out by two different people, this will lead to additional costs. In particular, the costs of fine-tuning execution of the two tasks between two (or more) people will result in transaction costs in this case. The time needed to brief a colleague about the work that has to be done might therefore not compensate for the gains achieved by separating the two tasks.[14]
To produce one unit of output, agent *i* needs $\tau_j(s,p)$ units of time to complete task *j*, where *j* = 1, 2. The time needed for both tasks depends on skills *s* and product characteristics *p*. Hence, the total time needed by agent *i* to produce one unit of output equals

$$\tau(s,p) = \tau_1(s,p) + \tau_2(s,p). \tag{1}$$

Now, define $\theta_s^j(s,p) = -\frac{\partial\tau_j(s,p)/\partial s}{\tau_j(s,p)}$[15] as the time for task *j* saved by a marginal increase in

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[12] Naturally, the boundary between what can be computerized at a given moment in time and what cannot, is vague. Huge investments and the use of a large number of programmers might ensure computerization of tasks that cannot usually be performed by a computer. However, we assume that the boundary between what can be computerized and what cannot, is a clear one. By generalizing our findings, it can be shown that if a more gradual transition is assumed, highly expensive automation investments will be made under certain circumstances, while under other circumstances only cheaper applications will be used.

[13] An optician's job, for example, involves making and selling (sun)glasses. It is important for the optician to repair, cut and assemble the glasses with the utmost care (task 1). Additionally, she must be able to address the customers' wishes with accuracy and patience in order to be able to fulfil their demands and advise them on a good pair of glasses (task 2). Another example is a chief editor, who has to keep track of and process data that dictate the contents of a newspaper, magazine, or radio or television program (task 1). At the same time, it is important that he has the capacities to manage and inspire people to do their jobs well and cooperate as an editing team (task 2).

[14] For the time being, we assume that these transaction costs are high enough to exclude separation of task 1 and 2. In Section 5.2 we extend the model and show that changes in income and the introduction of technology might change the decisions regarding the division of tasks within a company.

[15] For convenience we will skip the indices *s* and *p* in the remainder of this paper, except in cases where new functions are introduced and where derivatives are explicitly taken into account.

skill s. Here, we assume that $\theta_s^j \geq 0$ because an increase in s leads to increased productivity. Since s might reflect both general and specific skills, time savings might vary between tasks.[16] Similarly, $\theta_p^j(s,p) \equiv \frac{\partial\tau_j(s,p)/\partial p}{\tau_j(s,p)}$ is defined as the extra time requirement for task j due to a marginal change in product characteristic p. In this setting, the production of a more advanced product does not necessarily mean that the time spent on both tasks will increase, i.e. $\theta_p^j \geq 0$ does not apply in all cases. As we will argue later in this section, more advanced products might also require a substitution from one task to the other. We assume, however, that the production of a more advanced product always requires more time for task 2 (the task that cannot be computerized) to be carried out, i.e. $\theta_p^2 \geq 0$.[17]

Since the time to perform task 1 and task 2 depends both on the skills of a worker and the product specifications, we distinguish four cases, two with respect to the skill requirements and two with respect to the product characteristics: (i) task 1 is a *routine task*, (ii) task 1 is a *skilled task*, (iii) task 1 and task 2 are *substitutes*, and (iv) task 1 and task 2 are *complements*.

Definition 1: Task 1 is a *routine task* for skill i, if the time saved by s_i to perform this task is less than the time saved to perform task 2, i.e.

$$\frac{-\partial\tau_1(s,p)/\partial s}{\tau_1(s,p)} < \frac{-\partial\tau_2(s,p)/\partial s}{\tau_2(s,p)} \quad \text{i.e.} \quad \theta_s^1 < \theta_s^2.$$

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[16] For example, a mathematician with high math skills might be able to perform a large number of tasks more rapidly than an unskilled worker, but the time gain will be particularly large when she has to solve a mathematical problem.

[17] In the case of the optician in footnote 13 this means that advising a client requires more time in case of a more advanced product, because the performance of a pair of glasses requires more time in terms of explaining the advantages and drawbacks and the eventual advice given to the customer. The time needed for the production of the glasses might increase as well. However, if task 1 also consists of certain standard procedures to order new glasses, by filling in a form, improved quality might mean that these standard procedures are being replaced by more personal interaction between the optician and her customer; thus, the time needed for task 2 might be reduced.

Definition 2: Task 1 is a *skilled task* for skills *i* if the time saved by *s* to perform this task is more than the time saved to perform task 2, i.e.

$$\frac{-\partial\tau_1(s,p)/\partial s}{\tau_1(s,p)} > \frac{-\partial\tau_2(s,p)/\partial s}{\tau_2(s,p)} \quad \text{i.e.} \quad \theta_s^1 > \theta_s^2.$$

It is reasonable to assume that in most cases the job aspects that can be computerized are routine tasks.[18] Autor, Levy and Murnane (2001) point out that whether or not a task can be computerized does not depend on the skill level, but mainly on the character of the cognitive process needed to perform a task. Hence, tasks which can be computerized are found in jobs at all skill levels. As a counter example in which task 1 is a skilled task they refer to a chess player. Thinking about algorithms for the next move can be computerized in theory, but at the same time it requires a huge number of skills from the chess player. Yet moving the chess pieces and intimidating the competitor (task 2) cannot (easily) be computerized. However, these cases are rare to the extent that we may assume that for the labor market as a whole the effects of cases in which task 1 is a routine job will prevail.

In a similar vein, the production time needed for both tasks depends on product characteristics that will be chosen by the firm in order to maximize profits. If the configuration of the product changes, the time required to perform task 1 and task 2 also changes.[19] Variations in these product characteristics therefore involve substitution between task 1 and task 2 and hence lead to the following definition:

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[18] For example, in the case of the optician, cutting glasses is a routine activity, while distilling the customer's wishes is different in each case and requires a great deal of attention. The same line of reasoning applies to the chief editor: sorting incoming information is a routine-based aspect of the job. However, ensuring that the other editors keep a sharp eye and encouraging cooperation and team spirit are aspects requiring a specific and different approach each time.

[19] Let us compare, for example, a fashion store where customers can come in and show their trousers to the shop assistant, who can help them to find a matching shirt, with a shop where customers have to go through a catalog, fill in a form and collect their order at the desk. In this example, the distinguishing product characteristic is the personal advice given by the shop assistant in the former and the catalog in the latter case. Another example might be the repair of a broken-down television set. In one workplace, a technician opens the set to look what caused the defect. When she finds the cause of the problem, she repairs it by replacing one component or, if that is not possible, by finding a creative solution to get the television set going again. In another workplace, the television set is treated as a combination of modules. The technician checks the modules and replaces any malfunctioning ones. If this does not solve the problem, he advises the customer to buy a new television set. In these two examples *p* represents personal advice and the level of diagnostic checking, respectively. Typically, the more these characteristics are included, both product characteristics require fewer routine tasks and more custom-made service.

Definition 3: Task 1 and task 2 are *substitutable tasks* with respect to product characteristic p if a change in the product characteristic shifts time requirements from one task to the other, i.e.

$$\frac{\partial\tau_1(s,p)/\partial p}{\tau_1(s,p)} < 0 \text{ and } \frac{\partial\tau_2(s,p)/\partial p}{\tau_2(s,p)} > 0 \quad \text{i.e.} \quad \varepsilon_p^1 < 0 \text{ and } \varepsilon_p^2 > 0.$$

Task 1 and task 2 could, however, also complement one another with respect to a certain product characteristic.[20] This leads to the final definition.

Definition 4: Task 1 and task 2 are *complementary tasks* with respect to product characteristic p if a change in the product characteristic changes time requirements for both tasks simultaneously in the same direction, i.e.

$$\frac{\partial\tau_1(s,p)/\partial p}{\tau_1(s,p)} > 0 \text{ and } \frac{\partial\tau_2(s,p)/\partial p}{\tau_2(s,p)} > 0 \quad \text{i.e.} \quad \varepsilon_p^1 > 0 \text{ and } \varepsilon_p^2 > 0.$$

These four definitions concerning the skill and product content of the job provide tools to analyze changing skill requirements and the production of goods and services.

If a firm pays a wage w to agent i, the costs k per unit of final output the firm incurs equal

(2) $$k = w(\tau_1 + \tau_2).$$

Since the wage depends on productivity, it is related to the time needed to perform each task. To compare different agents with different characteristics, we decompose wage differentials into (i) the pace at which a certain product is produced (or the time required to produce one unit of output, i.e. $\tau_1 + \tau_2$), and (ii) the price per efficiency unit of output, $q(p)$, which depends solely on the product characteristics. Now, for agent i's wage to reflect productivity the following identity must hold:

(3) $$\bar{w}(\tau_1 + \tau_2) \equiv q.$$

Agent i's actual wage w might however deviate from this productivity wage $\bar{w}$, because apart from productivity, wages are often also dependent on or correlated with, for example, gender, tenure and union membership. A situation in which w deviates from $\bar{w}$, by say ω, is represented by $w \sim \bar{w}\ \omega$ and leads to the following costs k to be incurred by the firm producing one unit of output by agent i:

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[20] A good example is the optician mentioned in footnote 13. Measuring more aspects of the eye will generate more precise information, but also requires more interaction between the optician and the customer. Similarly, a journalist who uses a larger database to gather information for an article also needs more time to write the article integrating all this information.

(4) $$k \; ' \; \bar{w}(\hat{o}_1 \% \hat{o}_2) \; \% \; \grave{u}\,(\hat{o}_1 \% \hat{o}_2) \; ' \; q \; \% \; \grave{u}\,(\hat{o}_1 \% \hat{o}_2).$$

The products produced by agent *i* are sold at price $\tilde{n}(p)$. Then, the profit per product unit produced by agent *i* is defined in a similar way as income minus expenditure and can be written as

(5) $$\text{Ð} \; ' \; \tilde{n} \; \& \; w(\hat{o}_1 \% \hat{o}_2).$$

The total production of agent *i* equals *P*. Hence, total demand for agent *i*'s services equals

(6) $$D \; ' \; P(\hat{o}_1 \% \hat{o}_2).$$

The skills required for this production process and the product specifications made can be viewed upon as the result of profit maximization at the hands of the firm. Since changing the skill requirements affects both productivity in task 1 and task 2, changes in the required skills are not profitable when

(7) $$\frac{\mathtt{M}\text{Ð}}{\mathtt{M}s} \; ' \; \frac{\mathtt{M}(\tilde{n}(p) \; \& \; w(s)(\hat{o}_1(s,p) \% \hat{o}_2(s,p)))}{\mathtt{M}s} \; ' \; 0.$$

The intuition behind this result is that if a firm hires a higher skilled worker *i*, its productivity and income ($\tilde{n}$) increase but the wage costs (*w*) the firm has to incur also increase.[21] This tradeoff between higher skills and higher wages, the partial derivative $\mathtt{M}w/\mathtt{M}s$, gives the firm's optimal skill choice, i.e.

(8) $$w\left(\frac{\mathtt{M}\hat{o}_1(s,p)}{\mathtt{M}s} \% \frac{\mathtt{M}\hat{o}_2(s,p)}{\mathtt{M}s}\right) \; ' \; \& \frac{\mathtt{M}w(s)}{\mathtt{M}s}(\hat{o}_1 \% \hat{o}_2).$$

After some rewriting we obtain the following expression from this derivative:

(9) $$\& \frac{\hat{o}_1}{\hat{o}_1 \% \hat{o}_2}\left(\frac{\mathtt{M}\hat{o}_1(s,p)/\mathtt{M}s}{\hat{o}_1}\right) \; \& \; \frac{\hat{o}_2}{\hat{o}_1 \% \hat{o}_2}\left(\frac{\mathtt{M}\hat{o}_2(s,p)/\mathtt{M}s}{\hat{o}_2}\right) \; ' \; \frac{\mathtt{M}w(s)/\mathtt{M}s}{w},$$

which equals

(10) $$\frac{\hat{o}_1}{\hat{o}_1 \% \hat{o}_2}\grave{e}_s^1 \; \% \; \frac{\hat{o}_2}{\hat{o}_1 \% \hat{o}_2}\grave{e}_s^2 \; ' \; \frac{\mathtt{M}w(s)/\mathtt{M}s}{w}.$$

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[21] If *s* is multi-dimensional, the equality in equation (7) holds for all these dimensions separately.

Equation (10) is an important result for our analysis because it reveals three factors determining the optimal skill level of the job of agent *i*: (i) an increase in the marginal wage costs of skills $((\mathrm{M}w/\mathrm{M}s)/w)$ leads to a decrease in demanded skill requirements,[22] (ii) an increase in the advantage of skilled workers in performing task *j* (i.e. and increase in $\grave{e}^j_s$) leads to an increase in demanded skill requirements, and (iii) a change in the relative weights of the two tasks in the production process ($\hat{o}_1/(\hat{o}_1\%\hat{o}_2)$ and $\hat{o}_2/(\hat{o}_1\%\hat{o}_2)$) leads to an increase in demanded skill requirements in the case of a shift towards a skilled task and leads to a decrease in demanded skill requirements in the case of a shift towards a routine task.[23]

Similar to equation (7), profit maximization implies that product specifications are optimal and that a change in product specifications does not increase profits if

$$\frac{\mathrm{M}\text{Đ}}{\mathrm{M}p} \text{ ' } \frac{\mathrm{M}(\tilde{n}(p)\ \&\ w(s)(\hat{o}_1(s,p)\%\hat{o}_2(s,p)))}{\mathrm{M}p} \text{ ' } 0, \tag{11}$$

in which the tradeoff between a more advanced product and a higher price, the partial derivative $\mathrm{M}\tilde{n}(p)/\mathrm{M}p$, gives the firm’s optimal product specifications, i.e.

$$w\left(\frac{\mathrm{M}\hat{o}_1(s,p)}{\mathrm{M}p}\%\frac{\mathrm{M}\hat{o}_2(s,p)}{\mathrm{M}p}\right) \text{ ' } \frac{\mathrm{M}\tilde{n}(p)}{\mathrm{M}p}. \tag{12}$$

Similar to equation (8), we can rewrite this as

$$\hat{o}_1\left(\frac{\mathrm{M}\hat{o}_1(s,p)/\mathrm{M}p}{\hat{o}_1}\right) \% \hat{o}_2\left(\frac{\mathrm{M}\hat{o}_2(s,p)/\mathrm{M}p}{\hat{o}_2}\right) \text{ ' } \frac{\mathrm{M}\tilde{n}(p)/\mathrm{M}p}{w}, \tag{13}$$

which equals

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22. This can be seen from the second-order condition. Since equation (10) reflects a maximum, the second-order condition equals

$$\frac{\mathrm{M}(\hat{o}_1/(\hat{o}_1\%\hat{o}_2)\grave{e}^1_s\ \%\hat{o}_2/(\hat{o}_1\%\hat{o}_2)\grave{e}^2_s)}{\mathrm{M}s} < \frac{\mathrm{M}(\mathrm{M}w(s)/\mathrm{M}s/w)}{\mathrm{M}s}.$$

This means that if *s* becomes more expensive, employers will diminish their skill demands.

23. Because the relationship between skill and productivity generally differs between both tasks, each task would have a different skill requirement if carried out by separate workers. Skill requirements for the routine task would be lower than skill requirements for the skilled task. Since we assume that both tasks can not be separated, this implies that the actual skill level is a compromise between the skill levels that are optimal for these tasks separately. The skill level resulting from this compromise depends on the time needed for each task. A change in the relative time required for each task affects the weighting of these effects and therefore influences the recruitment decision.

$$\tau_1 \theta^1_p + \tau_2 \theta^2_p = \frac{\partial\rho(p)/\partial p}{w}. \qquad (14)$$

As in the case of optimal skill demand, the weighted average of the extra time needed for production in order to increase product quality *p* determines the optimal product specification. The major difference with the optimal skill equation is that rather than the relative time spent on each task, the absolute amount of time needed determines this equilibrium. If wages increase or if the price increase of a more advanced product diminishes, the optimal amount of time available to produce a product falls. This means that product quality measured in terms of *p* will go down both if task 1 is a routine task and if task 1 and 2 complement one another. In the first case, this means that agent *i*'s production time shifts from task 2 to task 1, while in the second case agent *i*'s time spent on both tasks diminishes.[24]

3 A model of computerization

The basic approach of the previous section describes the production costs of a job that consists of two tasks and puts forward its skill requirements and product characteristics as a profit optimizing decision of the firm. This model enables us to perform a hypothetical experiment, which we turn to now. Consider two agents, *T* and *U*, who are identical in their skill level *s* and produce the same product with characteristics *p*. Now suppose agent *T* gets a computer to perform task 1 and agent *U* continues to perform task 1 without a computer.[25]

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[24] Equation (14) provides an interesting link between the marginal product price and the marginal price per efficiency unit of production because wages are endogenous in the model. This yields the following equation:

$$\frac{\partial q(p)}{\partial p} + \omega\left(\frac{\partial\tau_1(s,p)}{\partial p} + \frac{\partial\tau_2(s,p)}{\partial p}\right) = \frac{\partial\rho(p)}{\partial p}.$$

If agent *i*'s actual wage w reflects marginal productivity $\omega = 0$ and $w = \bar{w}$, so this equation equals equation (14). However, if agent *i*'s actual wage lies above marginal productivity, i.e. $w = \bar{w} + \omega$, profit per product unit remains the same, but the product price exceeds the marginal price per efficiency unit by $\omega((\partial\tau_1(s,p)/\partial p) + (\partial\tau_2(s,p)/\partial p))$.

[25] Let us take as an example a writer who has to think about the story she wants to tell (task 2) but also has to put down her thoughts one way or another to codify the ideas, either by using a pen or a dicta-phone (task 1). Another example might be a truck driver who has to read a map to get from the loading-berth to the place where he has to unload (task 1), but also has to drive his truck safely (task 2). In the first example, writer *T* might be given a word-processing software package to write down the ideas, while writer *U* continues to put the story on paper using a pen. In the second case, truck driver *T* is now using a geographic positioning system (GPS) to decide which road is optimal given the distribution of traffic at that moment and truck driver *U* still uses a road map. In these examples, the writer still has to come up with original thoughts and the truck driver still has to drive the truck (task 2). By the same token, the optician and chief editor discussed in the previous section also perform tasks that can be computerized. In the case of optician *T* the preparation of glasses is automated by using computerized equipment. Similarly, the Internet assists chief editor *T* in

This experiment implies that agent *T* no longer have to perform task 1 directly or manually. Instead, he has to operate a computer which assists him to perform this aspect of the job. To operate the computer takes time $\tau_c(s,p)$, which depends on *s* because using a computer might require skills and the time involved to operate the computer might therefore vary with the skills of the worker; τ_c also depends on *p* because due to the different characteristics of different products and production processes, the production of one good can more easily be automated than that of another product. Computerization of task 1 might also have (a more indirect) impact on the time required to perform task 2. If the good produced and the way it is produced – either by man or by computer – remains unchanged, there is in fact no reason why the time required for task 2 should change. However, in the literature the complementarity between computers and particular human tasks is generally regarded as an important route for changing configurations of jobs and skill-biased technical change. In this setting, such a complementary relationship arises once a firm uses the possibilities of a computer to change the characteristics *p* of the product or production process. For the time being, we just allow the time needed to perform task 2 to change as a result of computerization:[26] $\hat{\tau}_2 = \tau_2 + \Delta$. If $\Delta < 0$, $\hat{\tau}_2 < \tau_2$ and if $\Delta > 0$, $\hat{\tau}_2 > \tau_2$. In the case where $\hat{\tau}_2 < \tau_2$ computerization of task 1 results in less time required to perform task 2; more time to perform task 2 is required when computerization of task 1 leads to $\hat{\tau}_2 > \tau_2$. In general, the time agent *T* needs to produce one unit of output equals

$$\tau_T = \tau_c + \hat{\tau}_2, \tag{15}$$

whereas agent *U* needs production time equal to equation (1), i.e. $\tau_U = \tau_1 + \tau_2$. Note that $\tau_T < \tau_U$ if $\tau_c + \hat{\tau}_2 < \tau_1 + \tau_2$.[27]

Now, if we suppose that the same person with the same qualifications continues to be employed on this job and that the wages for these qualifications remain the same (reflecting a true small-size experiment), the introduction of the computer changes the costs incurred by the employer as defined in equation (2) by $(w+c)(\tau_c + \hat{\tau}_2) - w(\tau_1 + \tau_2)$ to

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gathering information more efficiently, and a word-processing and typesetting package helps editor *T* to put the information in the right format to smooth publication.

[26] In Section 4.3 we will go into more detail on this issue.

[27] To describe the case where computerization leads to less time spent on the job as a whole, i.e. $\tau_c + \hat{\tau}_2 < \tau_1 + \tau_2$ we need $\tau_c < \tau_1$ and/or $\hat{\tau}_2 \leq \tau_2$.

$$k_T = (w+c)(\tau_c+\tau_2), \tag{16}$$

where *c* reflects the costs of computer use by agent *T*. These costs can be thought of as maintenance, depreciation and operating costs, but also as costs for buying new software applications and hardware. The total costs the employer has to incur when he gives agent *T* a computer are higher than the costs of not giving him one if $c(\tau_c+\tau_2) > w(\tau_1+\tau_2) - w(\tau_c+\tau_2)$. An important assumption of the model is that the costs of the equipment are related to the time agent *T* needs to finish the manufacturing of one product. This assumption reflects an essential characteristic of the way in which computers, and PCs in particular, are currently used in the workplace. After all, the part of the working time the computer is actually used depends mainly on the time the employee needs to fulfil the computerized task.[28] Implicitly we also assume that *c* has to be paid for the entire duration of the whole working time, which essentially means one machine per each employee. This means that the computer is out of use or waiting to be used, when agent *T* is performing task 2. The interrelatedness between the two tasks and the assumption that one person has to carry out the job makes this assumption realistic.[29]

3.1 When is the computer introduced?

If computers are not randomly assigned to agent *T* but firms are free to invest in computers, the decision to introduce a computer depends on the costs involved to computerize some part of the job. This decision is based on the break-even point at which the firm's profits are the same for agent *T*, who uses a computer to perform task 1, and agent *U*, who does not use a computer to complete task 1. After combining and rewriting equation (2) and (16), the break-even point *b*, at which $c(\tau_c+\tau_2) = w(\tau_1+\tau_2) - w(\tau_c+\tau_2)$, equals

$$b = w\left(\frac{\tau_1+\tau_2}{\tau_c+\tau_2} - 1\right). \tag{17}$$

The interpretation of equation (17) is the following. If $b > c$, a computer is profitable because the actual costs of the computerization of task 1 are below the break-even point. Allowing for some randomness in the actual costs of computer use ($c = \hat{c}+\varepsilon$, where ε is an error term with the usual assumptions), a higher *b* can be interpreted as a higher probability that task 1 is carried out by making use of computerized equipment, i.e. $P(computer) = P(b>c)$.

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[28] Previously, the calculation speed of the computer was the main limiting factor in the efficiency of the performance of the computerized task, but this type of situations are now rare. The reason for this is that there are few computer applications requiring the employee to give instructions so that she can attend to other tasks until the computer has completed the task.

[29] In footnote 30 we show that the results of our model are the same if this assumption is relaxed.

The essence of equation (17) is that higher wages increase the probability of using a computer. For a good interpretation of equation (17), it is important to know why wages differ between employees. To examine the impact of these differences on the introduction of the computer, the relationship between the pace of production and wages, as articulated in equation (4), can be incorporated into equation (17). This leads to the following break-even decision to introduce a computer:

$$b = \frac{(\omega(\tau_1+\tau_2)+q)}{(\tau_c+\tau_2)}\left(1-\frac{\tau_c+\tau_2}{\tau_1+\tau_2}\right). \tag{18}$$

This equation consists of three interesting parts. First, $\omega(\tau_1+\tau_2)+q$ brings about the influence of wages on computer use. Secondly, $\tau_c+\tau_2$ represents the amount of time the computer is needed for each product to be produced. Finally, $1-(\tau_c+\tau_2)/(\tau_1+\tau_2)$ represents the time gain of using a computer to perform task 1.[30]

By changing the assumptions underlying the model we are able to derive these three parts of equation (18) separately. This enables us to make explicit several discussions in the literature about computer use and to illustrate the meaning of these three components in detail. First, let us assume that the costs of computer use depend only on the advancement of the product produced, such that a doubling of the advancement would also double the costs of computer use in terms of efficiency units of output, i.e. $w(\tau_c+\tau_2)+cq$. Given that wages perfectly reflect productivity, the break-even point would be proportional to the first term of equation (18), i.e.

$$b = \left(1-\frac{\tau_c+\tau_2}{\tau_1+\tau_2}\right). \tag{19}$$

Assuming that the job consists of only one task ($\tau_2 = \tau_2 = 0$), equation (19) results into $b = (1-\tau_c/\tau_1)$. This simplification of equation (19) has three interesting implications because it demonstrates that the introduction of the computer to perform task 1 depends on the skill level of

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[30] Note that if the computer is only needed to perform task 1 or just a part of the time to carry out task 2 (with λ reflecting this fraction), the expression for the break-even cost becomes

$$b = \left(\frac{\omega(\tau_1+\tau_2)+q}{\tau_c+\lambda\tau_2}\right)\left(1-\frac{\tau_c+\tau_2}{\tau_1+\tau_2}\right).$$

The gain from only using the computer for some time further increases the benefits of introducing a computer. The use of the computer in this case often leads to a situation in which more than one employee makes use of one single computer. This is common, for example, in clothing stores, where a computerized cash register is used the moment a salesperson sells an item. The same cash register is used by a colleague selling an item to another customer.

the worker in a specific job. First, if task 1 becomes more routinized due to computerization (as an extreme case one could imagine that $\tau_c(s,p)$ is constant in *s*), the ratio τ_c/τ_1 is increasing in skill level, so the introduction of the computer is most profitable for jobs in which routine tasks are prevailing, i.e. in unskilled jobs. This is by and large in accordance with the argument underlying the fear of de-skilling the workforce as a result of computerization as perceived in the 1970s (see Braverman, 1974 and Freeman and Soete, 1994 for an overview). Second, if the computerization of task 1 is skill-neutral (i.e. τ_c/τ_1 is constant in *s*), the time gain for skilled workers equals the time gain for unskilled workers and nothing changes. Finally, the observation that computers are used mainly among skilled workers might lead to the conclusion that skilled workers gain proportionally more from computer use than unskilled workers. This indicates that the productivity of agent *T* depends more on his skill level than the productivity of agent *U*, which is consistent with the observation that computer skills are highly valued and that the computer can be regarded as a direct source of skill-biased technical change and the dispersion of wages.

However, most workers do not seem to spend their working time on operating a computer only. They merely use the computerized equipment for some job aspects, which in most cases is a relatively small fraction of the total working time. As a consequence, even if operating a computer requires a high level of computer skills and even if computers are mainly used in high-skilled jobs, its effect on the use of computerized equipment is largely offset by the time needed for other tasks that are part of the job. This can be easily seen from our configuration of two tasks because $(\tau_c+\tau_2)/(\tau_1+\tau_2)$ goes to unity when the time needed for task 2 becomes relatively more important. For that reason, several authors have focused on the job aspects included in task 2 and have stressed the importance of the skills needed to complement the use of the computer (e.g., Levy and Murnane, 1996). The main thesis put forward in these studies is that skilled workers profit in particular from the computerized equipment in task 1, because of the complementarity between the computerized task 1 and task 2 (in terms of equation (15) task 2 becomes more skilled) and not necessarily because it reduces the time needed to perform task 1 more for skilled workers than for unskilled workers.

Before returning to the assumptions about the costs of using a computer, one might ask what the effects on the break-even decision of the firm would be if wages do not fully reflect productivity. If, as elaborated in equation (4), $w = \bar{w} + \omega$, the break-even point for computer use becomes

$$b = (\omega\,(\tau_1+\tau_2)+1)\left(1-\frac{\tau_c+\tau_2}{\tau_1+\tau_2}\right). \tag{20}$$

This implies that workers with relatively high wages, compared to their productivity, have a higher probability to get a computer. This is simply the case because the employer paying such a wage has a larger incentive to save on expensive working time.

Because it seems to be implausible to argue that the cost of computers are directly dependent on the value of the product produced the model leads us to the second building stone of equation (18). For example, an excellent novel writer does not require a more advanced PC than the journalist of some local newspaper. Hence, although the written texts delivered by both persons differ to a large extent with respect to quality and speed, it is most likely that the costs of the PC they both use are quite similar. Assuming that computer costs are constant for each unit of product $(w(\hat{\tau}_c + \hat{\tau}_2) + c)$ therefore leads to inclusion of the second part of equation (18), i.e.

$$(21) \qquad b = (\omega(\hat{\tau}_1 + \hat{\tau}_2) + q)\left(1 - \frac{\hat{\tau}_c + \hat{\tau}_2}{\hat{\tau}_1 + \hat{\tau}_2}\right).$$

This equation implies that computer use is not only predicted by wages that deviate from the productivity wage (as in equation (20)), but also by products that are more valuable on the market. Workers earning higher wages, simply because they work faster before computerization, do not have a higher probability to get a computer. Because of higher wages the time saved will be more valuable, but at the same time, less time is saved due to the higher pace before computerization of task 1.[31]

Finally, when we assumed the costs of a computer to be proportional to the production time we once again obtain equation (13). Now, the probability that a computer is introduced can be written as

$$(22) \qquad P(computer) = P(b > c) = P\left(\left(\frac{\omega(\hat{\tau}_1 + \hat{\tau}_2) + q}{\hat{\tau}_c + \hat{\tau}_2}\right)\left(1 - \frac{\hat{\tau}_c + \hat{\tau}_2}{\hat{\tau}_1 + \hat{\tau}_2}\right) - c > 0\right).$$

3.2 The further diffusion of computers

Computers and computerized equipment are not only used by the high-wage workers anymore. Using the October supplements of the Current Population Surveys, it is interesting to note that workers with lower levels of education experienced a slightly more rapid increase in computer use than the higher educated workers. For example, computer use for workers with at least a college

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[31] Weinberg's (2000) observation that women are more likely to work with a computer than men, fits nicely into this result. Weinberg assumes that women faced a relative disadvantage in many jobs before computerization, due to physical job requirements. Lower wages for women, which might reflect this initial disadvantage, will not hamper computer introduction, because due to this productivity disadvantage, women's work is more likely be computerized.

degree increased from 42.1 percent in 1984 to 76.8 percent in 1997, whereas computer use among workers with only a high school diploma increased from 19.2 percent to 38.7 percent. In fact, from 1984 to 1997 the workers with an educational level of less than high school using a computer at work more than doubled from 5.1 percent to 12.6 percent. This suggests that while computers were mainly used by skilled workers initially, the diffusion of this technology to lower skilled workers becomes common. Following equation (18) the diffusion of the computer at the workplace can be attributed to three developments: (i) the development of new applications, software and hardware, which influence the productivity of computerized production ($\hat{o}_c$ versus $\hat{o}_1$ and indirectly also $\hat{o}_2$ versus $\hat{o}_2$), (ii) the decline in the cost of computerized equipment, and (iii) the changing wage distribution itself.

With respect to the first point, it seems evident that certain tasks are more suited to computerization than others. Of course, particularly in the case of tasks requiring information to be managed in a straightforward way (such as reading, writing, checking, or registration), time can be gained by using a computer and/or an appropriate application. However, an increasing number of applications have been developed for tasks that were thought to be less easy to computerize in the past (e.g., mathematical analyses in Mathematica and translation work). An efficient computer application is a *conditio sine qua non* for profitable computerization. As long as $\hat{o}_c \% \hat{o}_2 > \hat{o}_1 \% \hat{o}_2$, production without a computer is preferred, no matter how high the wages of these workers are. Considering the division of the ratio $(\hat{o}_c \% \hat{o}_2)/(\hat{o}_1 \% \hat{o}_2)$ for all tasks in the labor market, it seems plausible that the introduction of new applications will lead to a less disperse wage distribution. The more tasks become suited to computerization, the more the wage (in relation to computer costs) becomes the decisive factor in implementing a computer at work or not. This partially explains the tendency for the so-called computer wage premium to increase, as reported, among others, by Krueger (1993) and DiNardo and Pischke (1997). Krueger's (1993) finding that tasks like email and word-processing have a high wage premium can also be understood from this perspective. Since these are tasks which are relevant for a large fraction of jobs, the wage rather than job characteristics seems to be the decisive factor determining computer introduction for these kinds of use.

Greenwood and Yorukoglu (1997) provide interesting figures in which they show that the price of new equipment has fallen dramatically since the early 1970s and that the share of IT investment has risen from about 10 percent in 1970 to some 40 percent in 1990. Of course, this fall in the price of new equipment has led to lower costs for employers to introduce computers and hence to its widespread diffusion. The exact decline in the cost of computerized equipment is hard to monitor and only few figures are available on the micro level. Nevertheless, the European Information Technology Observatory (EITO, 2000) supplies figures showing that the price of a PC running on a Pentium processor of 101 to 149 MHz fell from 4,217 Euro in 1993 to 1,558 Euro in 1998.

Similarly, the price of a PC running on a Pentium II processor of more than 400 MHz declined from 1,956 Euro in 1998 to 1,335 Euro in early 2001. Lower computer costs will certainly increase computer use, among both skilled and unskilled workers. The major question is, however, whether mainly skilled workers – being more familiar with computers – will benefit more from these developments than unskilled workers, or that unskilled workers will gain from increased productivity in a similar vein as mainly skilled workers have done until now.

From our model it follows that a firm adopts computerized equipment to support agent T on task 1 when b exceeds the actual cost of the equipment. *Ceteris paribus*, the decrease in the costs c of computers experienced in recent decades increases the probability of computer use. The fall in the costs has directly affected both workers that already used a computer and those who started to use one because the profits of computer use increase as computer costs continue to fall. Once the computer is introduced, every decrease in computer costs will also decrease the firm's costs, while other costs and the worker's productivity remain unaffected (hereby abstracting from indirect market effects). In a small experiment, wages will of course remain unchanged, because the worker involved has to compete with a pool of workers with similar characteristics for which productivity remains the same; all productivity gains therefore increase the firm's profits. If all firms for which it is profitable to introduce computers will make a computer available to all its workers, a new equilibrium wage will settle. Assuming that the increased demand for computers will not increase costs, competition on the product market causes profit differentials between firms in this equilibrium to be absorbed by higher wages and/or lower product prices, depending on the elasticities of supply and demand. Assuming no systematic differences in these elasticities between different skill levels, profits per dollar wage costs – after deduction of the costs of computer use – are therefore good indicators of the wage differentials between different categories of workers once a new market equilibrium has been established.[32] Note that as personal characteristics rather than computer use itself will be rewarded in equilibrium, the same wage effects will be found for similar workers who are not using a computer. After all, if a firm requiring a skilled worker for a job without a computer is not willing to pay the same wage as another firm that does use computers, the worker will be lured into the computer-using firm.

Figure 1

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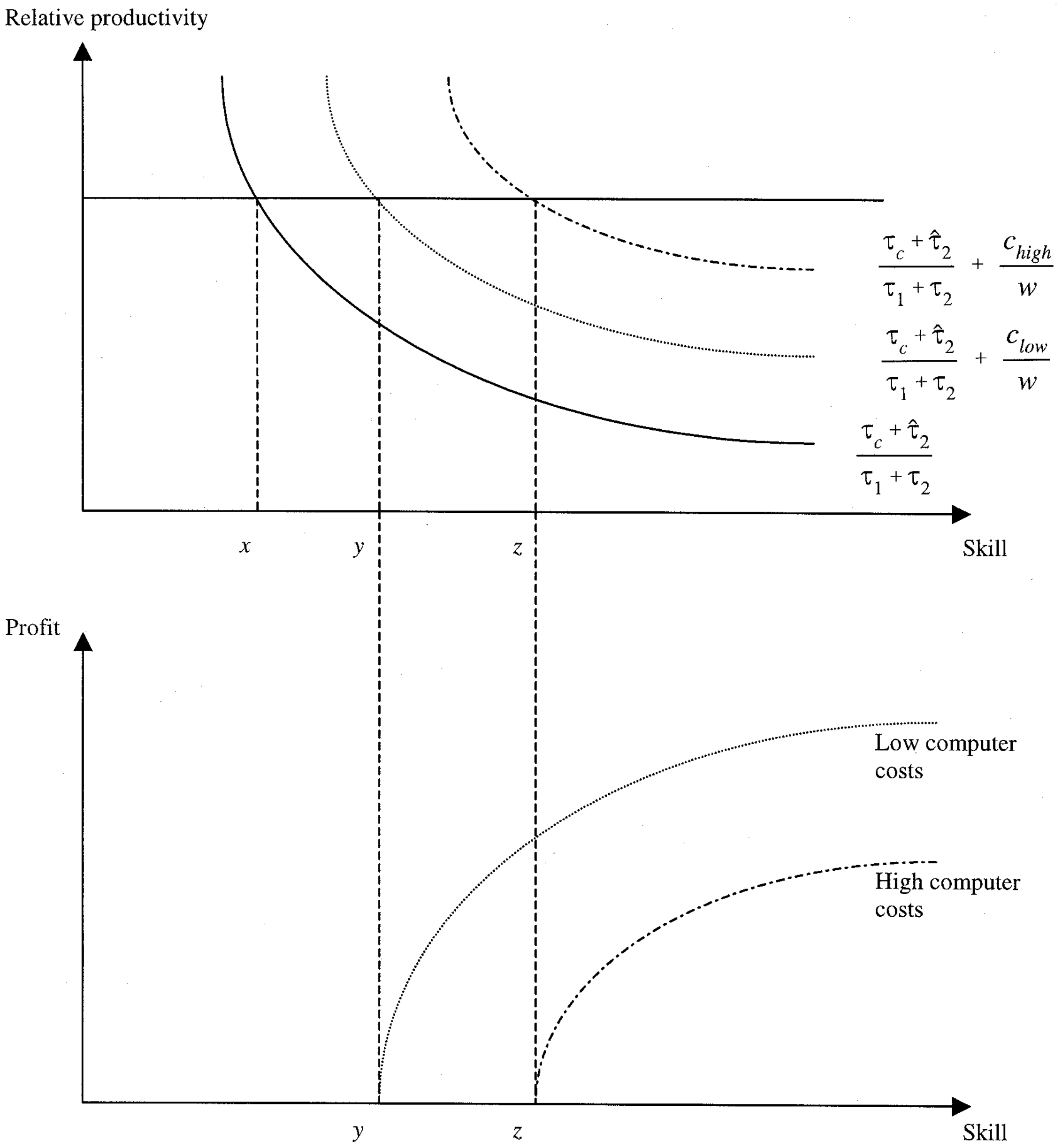
[32] In Section 4.1 we will show that computer use itself might lower wages due to increased productivity. However, within the group of computer users these productivity effects will not alter the wage differentials.



Now how will the further diffusion of computers affect skilled and unskilled workers? The answer to this question depends on how we interpret the typical empirical finding that computer use is relatively high among skilled workers and that computer users earn higher wages than non-users even after controlling for many job, personal and sector characteristics. Crucial to the explanation of these wage differentials is whether computer use is the result of a bias in the embodiment skills (either computer skills or complementary skills), as in equation (19), or whether wage costs are able to explain the lead taken by skilled computer-using workers, as in equation (18).

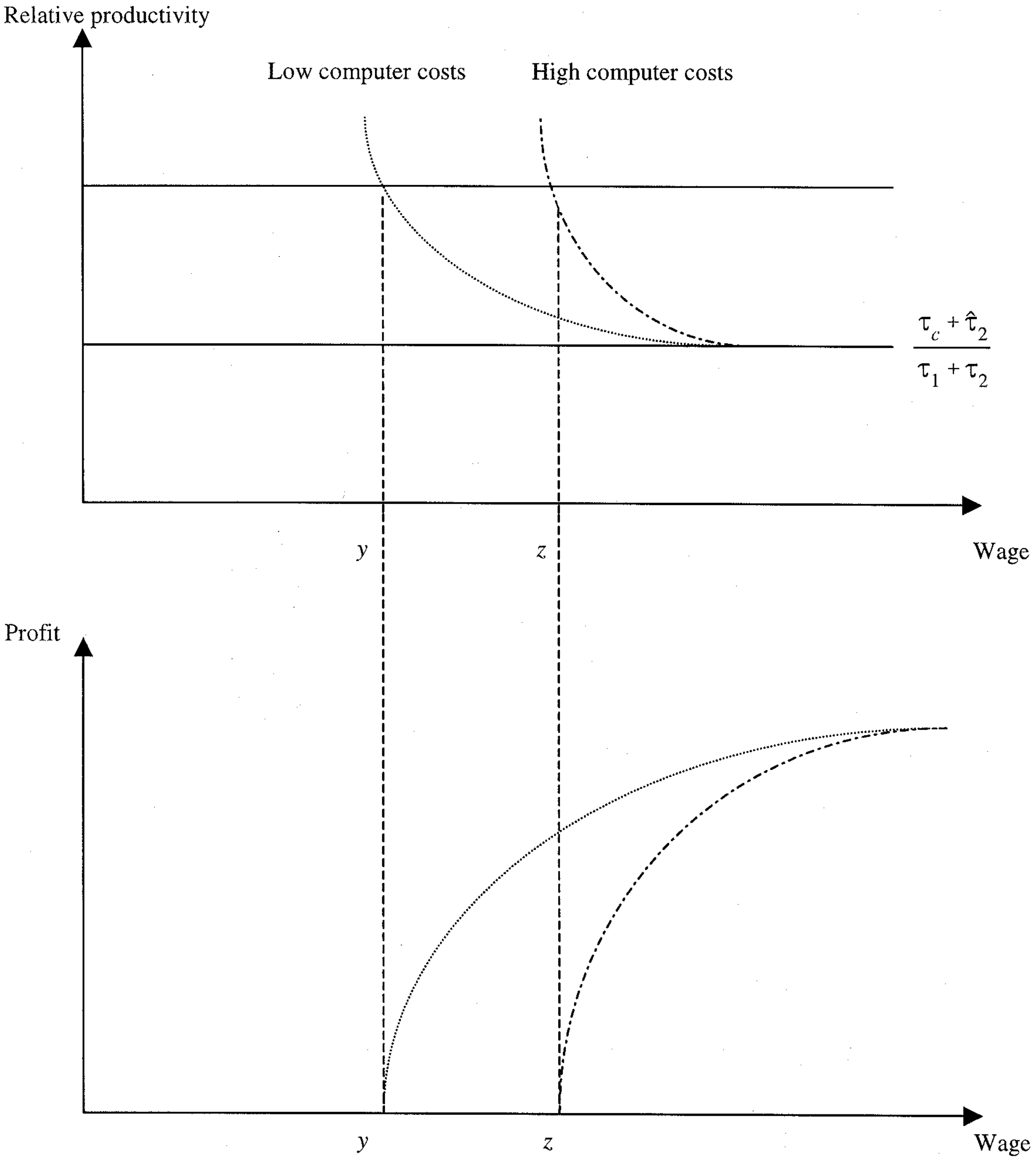
Let us start by analyzing the first interpretation. According to equation (19), differences in the probability of computer use are explained by differences in the factor $(\hat{o}_c \% \hat{o}_2)/(\hat{o}_1 \% \hat{o}_2)$. This factor therefore has to be decreasing in skills as shown in the first panel of Figure 1.

If $c\,6\,0$, the introduction of a computer is worthwhile starting from a skill level of *x*, i.e. the level at which the agent needs an equal amount of time to perform the job with a computer as he does without one ($(\hat{o}_c \% \hat{o}_2)/(\hat{o}_1 \% \hat{o}_2)\ '\ 1$). Since the unit of measurement in the graph is one expressed in time units, *c* has to be divided by the wage to be comparable in different situations. In addition, we assumed that computer costs are proportional to the productivity of a worker. We therefore added a constant factor in the graph to the productivity line to represent total costs. Now it can be seen that in a situation in which computer costs are high, the break-even decision is at skill level *z*. With a relatively low (but still positive) *c*, this break-even point is reached at point *y*.

The second panel of Figure 1 shows the changes in profits for the firm per unit of time worked in the situation where *c* is relatively high and in one where *c* is relatively low. This panel shows that the firm's profits are increasing in the skill level of its workforce. We also observe that if *c* drops, the further diffusion of computers leads to a profit increase which is similar for all workers. In other words, the introduction of computers among lower skilled workers seems to further increase the wages of higher skilled workers because their (computer or complementary) skills become an increasingly scarce factor.

These patterns become rather different if the concentration of computer use among skilled workers is explained by wage considerations, i.e. if it is assumed that *c* is mainly determined by the fraction of production time a computer is used. The graphical analysis of this argument is shown in Figure 2. In this case the productivity gain for computer use is constant in terms of time units. Since *c* is equal per unit of time, its relatedness to the wage decreases in wages, explaining computer use restricted to wages of at least *z* if computer costs are high and at least *y* if they are low. There are two important differences compared to the situation sketched in Figure 1. First, there is no longer a saturation point *x* beyond which workers will never use a computer, even when $c\,6\,0$: ultimately everyone will use a computer to carry out task 1. Secondly, Panel B of Figure 2 shows that, in contrast to the pattern shown in Panel B of Figure 1, the profits of using a computer converge to a constant rate. Contrary to Figure 1, the major increases in profits are for the new computer users. For workers that already used a computer, the profit reaches a maximum at the point where computer costs are negligible compared to their wage. Within the group of computer users, changes in relative wage differentials are comparatively small and fully disappear if $c\,6\,0$.

Figure 2



Whether one assumes skills or wages to be the explanation for computer use in the upper segment of the labor market, in an equilibrium framework, the wages of these workers will always tend to rise initially. However, the skill argument seems to imply that with the further diffusion of computers, skilled workers will continue to gain from their skills, and although computers might also be made available to unskilled workers, the financial gains will mainly go to the skilled workers. In the long run, this will create a “digital divide” between workers with high computer skills on the one hand and those with low computer skills on the other. The latter group is able to use this technology only with large difficulties or may never get a computer at work.

If it is assumed that the wage itself is the main reason for the unequal distribution of computers over the labor market, computer diffusion might move through the labor market and consequently through the wage distribution, if computers become sufficiently cheap. In such a scenario, high-wage workers will initially face a wage increase, but with the further diffusion of computers this group will not benefit further. Furthermore, lower-wage groups will experience similar wage increases, until in the theoretical end of the wage distribution every worker will use a computer, and every worker will have received a similar wage increase (in percentages).

It is interesting to note that according to equation (18), computer use is affected not only by changes in the costs of computers but also by changes in wages themselves. This implies that an increase in average wages will stimulate computer use at work. Since computers are mainly used by high earners, a change in the wage distribution might also affect total computer use. As long as a minority of workers use a computer, increased wage dispersion – at a constant average wage – will increase computer use, whereas if a majority of the workers use a computer, a decrease in the dispersion will positively affect computer use. A comparison of the United States and Germany between 1984/5 and 1992/3 shows that the much higher pace of diffusion in the United States (21 percentage points) is mainly due to a changing wage distribution. If the wage distribution is kept constant, the changing probability of computer use at each wage level accounts for only a 8-9 percent increase in both the United States and Germany.[33]

4 Implications for labor and product markets

In the previous section we discussed what happened when agent *T* got a computer in a model reflecting the true nature of a small experiment because the experiment did not influence market prices and wages. Furthermore, agent *T*’s job was not threatened and his tasks remained essentially the same. This experimental design enabled us to focus on the way a computer directly changed the

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[33] See Borghans and Ter Weel (2001) for such an analysis. Caselli and Coleman II (2001) also investigate computer adoption. They do so by relating data on imports of computer equipment for a large number of countries between 1970 and 1990. Their findings suggest that computer adoption is strongly related to human capital levels and international trade. Since they do not have data on the wage distribution, they are not able to investigate how computers have diffused through the wage distribution in the countries they investigate.

tasks of a worker. However, once the computer is introduced, this might have an impact on the decision making of the firm and if many firms change their production decisions this influences both the labor and goods market equilibrium. First, if the quantity of goods produced is kept unchanged, the productivity gain of the computer influences the demand for labor directly. Second, the product price is also influenced by computerization and hence the demand for the product changes. This changing demand for goods might lead to a different production volume, which again affects the demand for labor (indirectly). Finally, the behavior of the firm is likely to have changed fundamentally resulting from the introduction of the computer.

In this section we show that even if the computer does not demand specific skill requirements, the firm does have incentives to upgrade its skill demand for workers who use a computer. Furthermore, product specifications are also expected to change as a result of the higher skilled workforce. We investigate these effects for the labor and the product market, skill requirements and product specifications.

4.1 Product market

If it is profitable for a firm to introduce a computer at agent *T*'s job, the time needed to produce decreases, i.e. $(\hat{o}_1 \% \hat{o}_2) > (\hat{o}_c \% \hat{o}_2)$. In the experiment – if we could prevent other firms to introduce a computer – this particular firm could lower its product price and expand its market share infinitely. On the other hand, by keeping the product price and total product demand equal, the production time needed to produce *P* falls. As a consequence, demand for labor in the firm goes down with the factor

$$\frac{\hat{o}_1 \% \hat{o}_2 \;\&\; (\hat{o}_c \% \hat{o}_2)}{\hat{o}_1 \% \hat{o}_2} < 1. \tag{23}$$

Equation (23) shows (if product and labor demand remain constant) the factor by which the firm's demand for agent *T* goes down because the time to manufacture *P* is reduced. If in a competitive labor market only this gain in productivity is incorporated, without any change in product demand, agent *T*'s wage falls.[34]

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[34] This result is in line with Acemoglu's (1998 and 2000) observation for the analysis of increasing demand for skilled workers relative to unskilled workers. Although it is often argued that increased productivity of skilled workers leads to increased demand and higher wages for skilled workers, he obtains that the actual

In general, an increase in productivity implies that production costs go down and when the computer is adopted in all jobs similar to agent *T*'s job, the market price for the good falls. More specifically, production costs are reduced by

$$(24)\qquad \left(\frac{\text{ù}\ (\text{ô}_1 \% \text{ô}_2)\ \%\ q}{\text{ô}_c \% \text{ô}_2}\right)\left(1\ \&\ \frac{\text{ô}_c \% \text{ô}_2}{\text{ô}_1 \% \text{ô}_2}\right)\ \&\ c.$$

This term is positive if the introduction of a computer is profitable for the firm. If a firm lowers the product price according to these production costs, product demand increases. As a consequence, there will be an indirect positive effect on labor demand depending on the elasticity of demand for this good ç, i.e.

$$(25)\qquad \text{ç}\left[\left(\frac{\text{ù}\ (\text{ô}_1 \% \text{ô}_2)\ \%\ q}{\text{ô}_c \% \text{ô}_2}\right)\left(1\ \&\ \frac{\text{ô}_c \% \text{ô}_2}{\text{ô}_1 \% \text{ô}_2}\right)\ \&\ c\right].$$

The total effect on labor demand depends on the total effect of the two counteracting effects. From equation (25), we note that the costs of computer use *c* influence the positive indirect labor demand effect of equation (24) but do not have an impact on the negative direct effect of equation (23). This can be understood as follows. When the costs of introducing a computer exactly match the costs of working without a computer, the productivity gain decreases the demand for labor. Since there are no gains in the costs, no additional demand will be created and the firm's profits remain equal. As discussed in Section 3.2, every further fall in computer costs keeps the productivity change unaltered, but lowers production costs, increases profits and enables the firm to increase goods demand by lowering prices. Now, if goods demand is very inelastic, in a new competitive equilibrium, prices are lower to bring profits back to zero. In contrast, if goods demand if very elastic, profits go down because the workers on the computerized jobs have to be paid higher wages. This is the effect described in Section 3.2 that given the fact that a job is computerized, workers in jobs close to the break-even point profit less (in percentages).

Since computers are initially introduced in high-wage jobs, computerization might lead to skill-biased technical change if the indirect effect exceeds the direct effect. The absence of intra-industry shifts in employment as a result of computerization suggests however that on average no such

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labor-market effects depend crucially on the elasticity of substitution between the goods these skilled workers produce and the goods unskilled workers produce. In the case of a Leontief production function – in which demand for one good will not react on a change in the price – demand for skilled labor falls, and thus their wages indeed fall. Acemoglu (2000) indicates that substitution on the goods market and substitution of labor within an industry together constitute the elasticity of substitution between two types of workers (in his setting skilled and unskilled workers). Since in this experiment we have until now kept the qualifications of the worker within a job fixed, only substitution at the goods market matters here.

demand shifts occur.[35] This effect can be compared to the elasticity of substitution between skilled (college graduates) and unskilled (high school graduates) workers. Katz and Murphy (1992) estimate the elasticity of substitution between college graduates and high school graduates to be about 1.4, which implies an increased demand for skilled workers when their productivity increases.[36] Acemoglu (2000) points out that this elasticity reflects both within job changes in the demand for skilled workers and demand shifts related to shifts on the product market. The part of the elasticity of substitution that matters here is related to product market shifts only. Thus, the introduction of computers might both lead to an increase and a decrease in the demand for labor in the sectors introducing computers. No empirical evidence is available that points towards increased goods demand or increasing sector volume as such due to computerization, which is consistent with our model that computers have not increased productivity differentials between more and less-skilled computer users. Furthermore, when computers become less expensive, job aspects at lower wage levels also become computerized and similar effects on demand might occur at such lower levels. Hence, although the introduction of the computer influences labor demand, there seems to be no reason to expect that it leads to skill-biased technical change via inter-industry shifts in employment.

4.2 Optimal skill requirements

In Section 2 we derived that the skills demanded by a firm for a certain job are determined by the trade-off between increased productivity due to higher skills and the higher wages people with more skills have to be paid. The introduction of the computer is likely to alter the value of skills and to change the optimal skill demand of the firm.

The main issue regarding the effect of computerization on skill requirements seems to be whether a firm changes its demand for skills. Equation (10) showed that skill requirements can be seen as a profit maximization decision of the firm. The following expression shows the optimal skills recruitment after computerization:

$$(26) \qquad \frac{\hat{o}_c}{\hat{o}_c \% \hat{\hat{o}}_2}\grave{e}_s^c \; \% \; \frac{\hat{\hat{o}}_2}{\hat{o}_c \% \hat{\hat{o}}_2}\hat{\grave{e}}_s^2 \;\; ' \;\; \frac{\mathtt{M}w(s)/\mathtt{M}s}{w}.$$

Keeping the wage structure constant, this means that the optimal skill requirements might change in three different ways as a result of the introduction of the computer.

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[35] See e.g., Autor, Katz and Krueger (1998).

[36] Other studies report values for the elasticity of substitution between college and high school equivalents between 1 and 2 (see Autor, Katz and Krueger, 1998 for a discussion).

First, if task 1 becomes a more-skilled task for which the relative time to produce depends more on skills than before the introduction of a computer, the firm demands higher-skilled workers because of the importance of computer skills. By examining the British labor market Borghans and Ter Weel (2000a) show that computer skills do not seem to possess value on the labor market if the computer is used to support work.[37] Since this is the case for most jobs, these findings are consistent with our argument that the computerized task is often a routine task that becomes even more routinized than before computerization. This implies that skill requirements might for this reason, *ceteris paribus*, even decrease.

Second, due the computerization of task 1, the performance of task 2 might demand a higher-skilled worker. This means that for complementarity reasons skilled workers relatively gain more time (or loose less time) than unskilled workers, after the introduction of the computer, to perform tasks 2. This argument is used by Levy and Murnane (1996) who examine the impact of computers on skill demands in the custodian unit of a large U.S. bank. They particularly address the question with what skills computers form a complementary relationship.

Third, even if the influence of skills on both tasks is kept constant, the weight of both influences changes after the introduction of the computer in task 1. This means that if task 1 is a routine task (Definition 1) skill requirements increase because the introduction of the computer puts more weight (in term of time units) on task 2. An important implication of this result is that for all jobs in which the computerized task is a routine task, the introduction of a computer seems to increase skill requirements, even if the effect of skills on both tasks separately is kept constant. This suggests that neither computer skills, nor arguments for the increasing importance of complementarity skills are needed to explain a skill bias in the recruitment decisions of firms for jobs in which the computer is introduced and/or used as found in many studies.

This third finding is novel to the literature in that it shows that even if working with a computer does not increase the comparative advantage of skilled workers in each task, skill requirements might nevertheless be raised. This effect might explain the difficulties in the search for a direct link between increased skill demand and technical change to explain skill-biased technical change, which arise from the fact that the focus was on the first two arguments underlying equation (10).[38] Second, our

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37. For jobs in which the computer is used to e.g. develop new applications computer skills are of course of central importance. This kind of computer utilization can be seen from a production perspective, i.e. the computer is used to develop itself further. In contrast, in most occupations in which a computer is utilized a support perspective holds, i.e. the computer is used to support certain job aspects.

38. For example, Autor, Katz and Krueger (1998) attribute the strong correlation between the rate of skill upgrading and computerization at the industry level to the fact that new technologies and skilled labor seem

framework is able to interpret the findings of Autor, Levy and Murnane (2001) who find that computers substitute for some routine job aspects and complement other job aspects which are non-routine tasks. Finally, the finding of Doms, Dunne and Troske (1997), that computer investment is uncorrelated with changes in average wages paid to either unskilled and skilled workers but highly correlated with the relative number of skilled workers, seems to be understood in terms of our arguments of the impact of computerization on the firm’s recruitment behavior: the implication of our model is that skill upgrading will take place at those jobs currently being computerized. Until the mid-1990s, computers have been mainly introduced in high-school level and college level jobs, which explains the shift in labor demand from high-school graduates to college graduates. With the further diffusion of computers this implies that skill upgrading might take place in unskilled jobs, leading to a shift in demand for unqualified workers as well.

4.3 The optimal product quality

After the introduction of a computer, an employer also reconsiders the configuration of the goods the firm produces. In equation (14) the optimality condition for the product specification is derived when agent *i* does not use a computer. After the introduction of the computer, this equilibrium condition becomes

$$\tau_c \theta_p^c + \hat{\tau}_2 \hat{\theta}_p^2 = \frac{\partial\rho(p)/\partial p}{w}. \tag{27}$$

Since the introduction of the computer reduces production time, either the time needed for task 1 or the time needed for task 2 diminishes, by assumption. The time required for task 2 depends positively on product quality and a reduction in production time due to complementarity between the two tasks lowers the marginal costs of a better product (see Definition 3 and 4). This induces a firm to improve product quality. A reduction in the time needed for task 1 could also lead to the opposite outcome. Since time needed for task 1 depends negatively on product quality if task 1 and 2 are substitutes (Definition 3), $\tau_c < \tau_1$ increases the marginal costs of extra product quality and provides incentives to the firm to lower product quality. In this case the product is based on a more routinized production process, which makes use of the advantages of the computer.

Computerization of task 1 leads to a change in the specifications of the product. By defining the new product specifications p^*, the time needed for task 1 and 2 now equals $\tau_c(s,p^*)$ and $\tau_2(s,p^*)$, respectively. Given these new product specifications employers might also have different incentives for the skill level they demand when $\tau_c(s,p^*) \neq \tau_c(s,p)$ and $\tau_2(s,p^*) \neq \tau_2(s,p)$. Furthermore, the

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to complement each other in a direct way.

derivatives $è_s^c$ and $\hat{è}_s^2$ might have different values at p^*. This notion provides another interpretation to the complementarity between computers and skills: Ä can now be interpreted as the difference between the time needed for task 1 for product p^* and product p. With Ä being positive, this would lead to a skill bias in labor demand if task 2 is a skilled task. An increase in $\hat{è}_s^2$ might further increase this skill bias.[39]

5 Extensions

5.1 Firm effects

The introduction of computers at work is not restricted to one individual worker, but probably related to a firm's behavior towards implementing new technologies thereby affecting the firm's workforce as a whole. Until now we assumed that firms decide upon computer investments for each worker separately, however. In practice it seems to be impossible to introduce a computer system at the workplace of the firm's high-wage workers, leaving the way the low-wage workers operate unaffected. Doms, Dunne and Troske (1997) and Dunne, Forster, Haltiwanger and Troske (2000) show indeed that all workers in firms that have implemented computerized equipment to assist the work receive higher wages than workers in firms that have not implemented such new technologies. Such findings suggest that, at the firm level, the correlation between computer use and wages is primarily due to the fact that firms with relatively high-wage workforces are more likely to adopt new technologies than firms with relatively low-wage workforces.

Our model can be extended to deal with the firm's decision upon implementing computerized equipment for its workforce. To do so, the additional profit from computerization changes into

$$(28) \qquad \left(\underset{i}{\mathbf{j}}\ w_i \% cNf(N)\right)\left(\underset{i}{\mathbf{j}}\ \hat{o}_c \% \underset{i}{\mathbf{j}}\ \hat{o}_2\right) \& \underset{i}{\mathbf{j}}\ w_i\left(\underset{i}{\mathbf{j}}\ \hat{o}_1 \% \underset{i}{\mathbf{j}}\ \hat{o}_2\right).$$

In this equation total wage costs rather than individual wage costs matter; total time spent on both tasks matters and computer costs per worker become lower if the number of employees increases. The function f describes the ratio between the actual costs per worker and the costs per worker in a one-worker firm. Hence, $f(1) = 1$ and since the costs per worker decrease in N, $f'(N) < 0$. In a similar fashion, the break-even costs b for computer use per worker now equal

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[39] Such an increase in $\hat{è}_s^2$ can also be interpreted from an extension with more than two tasks in which the change in product quality asks for more additional time in one non-computerized task than in another non-computerized task, with the first of these two tasks being more skilled than the second.

(29) $$b = \frac{1}{f(N)} \frac{\frac{1}{N}\sum_i w\left(\sum_i \tau_1 + \sum_i \tau_2\right) + q}{\sum_i \tau_c + \sum_i \tau_2} \left(1 - \frac{\sum_i \tau_c + \sum_i \tau_2}{\sum_i \tau_1 + \sum_i \tau_2}\right).$$

In this situation, three properties of the break-even decision change compared to the individual equation. First, the break-even point now depends on the level of average wages in the firm rather than on the level of some individual's wage. This means that a single low-wage worker within a firm, which pays on average high wages, might also get a computer because the machine is profitable to implement for his fellow workers. Second, the break-even point depends on the average time spend on each task rather than individual time. So workers who spend only a relatively small amount of their working time on task 1 might also get a computer. Third, the break-even point is increasing in firm size *N*. Hence, larger firms more easily introduce computers than smaller firms.

5.2 Working together

Firm characteristics rather than individual characteristics might not only affect the decision to invest in computerized equipment, but, once the computer is introduced, it might also affect the way in which workers cooperate or work together. An important assumption of our model is that one worker might perform different tasks, possibly with different skill requirements. This assumption has been justified by the observation that it might cost time to involve other workers in a certain activity. By making this argument more explicit, we show that the introduction of the computer seems to affect the way in which different workers within a firm operate together.

Consider task 1 to be a routine task (Definition 1). Furthermore, imagine a situation in which task 1 is carried out by an unskilled worker, while task 2 is carried out by a skilled worker. This is efficient if the time needed to instruct the unskilled worker to perform task 1 is recovered by the lower wage costs needed to bring to completion task 1, i.e.

(30) $$(\tau_2 + \tau_{instruct})w + \tau_1^{unskilled} w_{unskilled} < (\tau_1 + \tau_2)w$$

or

(31) $$\frac{\tau_1 - \tau_{instruct}}{\tau_1^{unskilled}} > \frac{w_{unskilled}}{w}.$$

From these expressions it can be observed that splitting the two tasks into two different jobs becomes more likely if (i) the wage differential between both workers is larger, (ii) instruction time is shorter, (iii) unskilled workers are relatively good at performing task 1 (i.e. task 1 is indeed an routine task) and (iv) task 1 is a relatively time consuming task.

The introduction of a computer changes the time needed for task 1 into the time needed for the computerized task, from $\hat{o}_1$ to $\hat{o}_c$. Now, the important question is whether after the introduction of the computer $\frac{\hat{o}_c \& \hat{o}_{instruct}}{\hat{o}_c^{unskilled}} > \frac{w_{unskilled}}{w}$ still holds. The answer to this question depends on (i) the reduction in time needed for the routine task, i.e. $\hat{o}_c$ versus $\hat{o}_1$ and (ii) on the time required for computer use by the unskilled worker relative to the skilled worker, i.e. $\hat{o}_c$ versus $\hat{o}_c^{unskilled}$. In a situation in which $\hat{o}_c^{unskilled} > \hat{o}_c^{skilled}$ it might be beneficial to undo the separation of tasks into two distinct jobs. However, if there is no skill bias in performing task 1 the fact that the time needed to operate a computer falls (rather than to carry out task 1), might lead to an integration of both tasks again. Computerization might therefore reduce cooperation between workers of different skill levels. Note that this reintegration process is more likely to occur if the wage differential between skilled and unskilled workers is smaller. Another interesting observation is that if this integration of routine tasks into a skilled job takes place, this reduces the tendency to increase the skill requirements within the job.

Kremer and Maskin (1997) and Acemoglu (1999) argue that there is not only a tendency towards a reduction in cooperation between skilled and unskilled workers, but at the same time an increase in cooperation between workers of equal skill level. From the above, it is not so straightforward to explain this tendency to work together in teams of similar skill levels. The changes described by Kremer and Maskin (1997) are driven by the notion that if the distribution of skills is sufficiently disperse, a further increase in the variance of skills induces skilled workers to work with other skilled workers and increase inequality. Acemoglu (1999) considers a model in which the supply of skilled workers reaches a critical number, so that it becomes profitable to change the composition of jobs and to create jobs designed only for skilled workers. In terms of our approach, such changes depend on the way in which team work influences the time requirements for certain activities and of the job in general. For example, a weekly meeting ($\hat{o}_{meet}$) in which workers discuss their experiences on their performance of task 2 might save an amount $\hat{o}_{team}$. This is only profitable when

(32) $$\hat{o}_1 \% \hat{o}_2 \& \hat{o}_{team} \% \frac{\hat{o}_{meet}}{h} (\hat{o}_1 \% \hat{o}_2 \& \hat{o}_{team}) < \hat{o}_1 \% \hat{o}_2,$$

i.e.

(33) $$1 \% \frac{\hat{o}_{meet}}{h} < \frac{\hat{o}_1 \% \hat{o}_2}{\hat{o}_1 \% \hat{o}_2 \& \hat{o}_{team}}.$$

The right-hand side of equation (33), indicating the relative amount of time needed without team working, increases when task 1 takes less time because of the implementation of computerized equipment. Team working only becomes profitable when the work becomes more concentrated on task 2. Hence, although we take a different route, our findings seem to go along with Kremer and Maskin's (1997) approach of diverging production processes among skilled and unskilled workers and Acemoglu's (1999) findings of changing composition of jobs within a firm.

5.3 Work intensity

The concentration of work on the skilled task 2 might not only affect the way in which workers cooperate, but also the intensity of their work. In the literature, computer use is often associated with work intensification. Effects of using a computer screen, but also the increased amount of information that has to be processed by workers are put forward as explanations for this. However, Lantz (1998) shows that workers who spend time on a computer to email do not suffer from a higher work intensity.

Our model offers an explanation for these two contrasting findings. It is often assumed that a job requiring higher skill levels is experienced as more intensive and it is also true that diversity in tasks reduces work intensity due to variety. According to our model, the introduction of the computer increases work intensity, because it generally increases the time spent on skilled tasks and reduces the time spent on routine tasks. The relatively more time spent on task 2 offers an explanation for the fact that work intensity increases and that computerization of the routine part of the job leads to some offsetting phenomenon captured by sending an email or browsing the Internet.

6 Conclusions

Computers have brought about a dramatic change in the labor market in the past decades. A large number of economists and commentators regard the introduction and implementation of the computer as a major determinant underlying the contemporary trend towards skill-biased technical change. They do so because the computerization of the labor market seems to go with increased skill upgrading and wage inequality. So far, computers have been used mainly by skilled workers and there has been a substantial wage differential between computer users and non-users. Therefore, it seems to be plausible that certain skills enable workers to make more effective use of the possibilities offered by a computer. Other results contradict these findings. This raises doubts about the specific way in which computers change the labor market.

In this paper we provide a simple model that is able to show what happens to skill demand, the production process, and the organization and intensity of work upon the introduction of computers at the workplace. Our results seem to be of interest for three reasons.

First, we show that Krueger's (1993) computer wage premium does not seem to be the result of the allocation of workers possessing the highest level skills to the most complex jobs, justifying doubts concerning the extent of this premium. In particular, we argue that the computer wage premium does not result from some spurious correlations or unobserved skills (e.g. DiNardo and Pischke, 1997). On the contrary, the computer wage premium seems to be a reflection of the opposite: it is more likely to be profitable for a firm to give a comparatively high-wage worker a computer because the efficiency gain is relatively larger than for a relatively low-wage worker. Hence, workers with relatively high wages have a higher probability to work with a computer than low-wage workers. Neither computer skills nor complementary skills are necessary to understand why computers are used by high-paid (and therefore high-skilled) workers; our argument merely runs through the cost of implementation of the computer. In other words, the use of computers by skilled workers and the computer wage premium are consistent with the finding that computer skills have no market value, as observed by Borghans and Ter Weel (2000a). Furthermore, from the same perspective these results offer an answer to the question why workers in firms operating advanced and new technologies earn higher wages (e.g. Doms, Dunne and Troske, 1997). Studies based on panel data which typically find that computers are introduced among high-wage workers first, but only lead to very modest wage increases afterwards, also fit to this framework, but have to be reinterpreted: rather than viewing high wages as a proxy for skills, these analyses seem to show that high wages lead to computer use.

The observation that it is unlikely that skills related to effective computer use explain the patterns of diffusion and wage differentials does not imply that computers are not a source of skill-biased technical change. In theory there are three reasons explaining the recent increase in the demand for skilled (college) workers. First, the demand for skilled workers might have increased because of the importance of the skills needed to operate a computer or because of skills complementary to the computer. Our model shows that this explanation is not the most likely one. Second, the productivity gain resulting from computerization reduces the price per efficiency unit of output and increases the demand for those products and hence skills. Since skill-biased technical change does not seem to be associated with inter-industry shifts in labor demand, this explanation of skill upgrading and wage inequality is also not a very likely one. Finally, our approach demonstrates that employers seem to upgrade their workforce because computerization enables firms to use high-skilled workers more effectively as a result of the diminishing importance of routine tasks. Thus, rather than decreasing the demand for unskilled workers and increasing the demand for skilled workers in general, the introduction of a computer seems to induce a gradual shift in skill requirements for jobs that are computerized. This latter channel is likely to be an important source of skill-biased technical change. The changing way in which workers can be deployed also leads to a better understanding of changes in work organization, product characteristics and work intensity.

Based on the model, as computers become cheaper and more applications become available, the majority of low-wage workers is also likely to be provided with a computer at work. Consequently, the current shift in demand from high-school graduates to college graduates might well change into a shift from workers without any degree to high-school graduates; so skill-biased technical change will be continued at lower ends of the labor market. It is likely that this continued skill bias will not be explicitly observed as a further increase in wage dispersion in the economy as a whole because it concerns wage shifts in the center of the wage distribution.[40]

References

Acemoglu, Daron (1998), Why do new technologies complement skills? Directed technical change and wage inequality, *Quarterly Journal of Economics*, vol. 113, pp. 1055-1090.

Acemoglu, Daron (1999), Changes in unemployment and wage inequality: An alternative theory and some evidence, *American Economic Review*, vol. 89, pp. 1259-1278.

Acemoglu, Daron (2000), Technical change, inequality and the labor market, NBER Working Paper 7800, July 2000.

Autor, David H., Katz, Lawrence F. and Krueger, Alan B. (1997), Computing inequality: Have computers changed the labor market?, NBER Working Paper 5956, March 1997.

Autor, David H., Katz, Lawrence F. and Krueger, Alan B. (1998), Computing inequality: Have computers changed the labor market?, *Quarterly Journal of Economics*, vol. 113, pp. 1169-1213.

Autor, David H., Levy, Frank and Murnane, Richard J. (2000), Upstairs, downstairs: computer-skill complementarity and computer-Labor substitution on two floors of a large bank, MIT Department of Economics Working Paper 00-23, September 2000.

Autor, David H., Levy, Frank and Murnane, Richard J. (2001), The skill content of recent technological change: an empirical exploration, MIT, mimeo January 2001.

Barras, Richard (1990), Interactive innovation in financial and business services: the vanguard of the service revolution, *Research Policy*, vol. 19, pp. 215-237.

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[40] Murhy and Welch (2001) indeed observe for the mid-1990s that wage dispersion in the United States for some groups is falling.

Bell, Brian D. (1996), Skill-biased technical change and wages: Evidence from a longitudinal data set, Nuffield College, mimeo March 1996.

Berman, Eli, Bound, John and Griliches, Zvi (1994), Changes in the demand for skilled labor within U.S. manufacturing industries, *Quarterly Journal of Economics*, vol. 109, pp. 367-398.

Berman, Eli, Bound, John and Machin, Stephen (1998), Implications of skill-biased technological change: International evidence, *Quarterly Journal of Economics*, vol. 113, pp. 1245-1279.

Berndt, Ernst R. and Morrison, Catherine, J. (1995), High-tech capital formation and economic performance in U.S. manufacturing industries: an exploratory analysis, *Journal of Econometrics*, vol. 65, pp. 9-43.

Borghans, Lex and Ter Weel, Bas (2000a), Do we need computer skills to use a computer? Evidence from the United Kingdom, ROA/MERIT, mimeo June 2000.

Borghans, Lex and Ter Weel, Bas (2000b), How computerization changes the UK labour market: The facts viewed from a new perspective, MERIT Research Memorandum 2000-026.

Borghans, Lex and Ter Weel, Bas (2001), The diffusion of computers through the labor market: Evidence from Europe and the United States, ROA/MERIT, mimeo January 2001.

Bound, John and Johnson, George (1992), Changes in the structure of wages in the 1980s: An evaluation of alternative explanations, *American Economic Review*, vol. 82, pp. 371-392.

Bresnahan, Timothy F. (1999), Computerisation and wage dispersion: An analytical reinterpretation, *Economic Journal*, vol. 109, pp. F390-F415.

Bresnahan, Timothy F., Brynjolfsson, Erik and Hitt, Lorin M. (1999), Information technology, workplace organization and the demand for skilled labor: firm-level evidence, MIT, mimeo May 1999, forthcoming *Quarterly Journal of Economics*.

Caroli, Eve and Van Reenen, John (2000), Skill biased organizational change? Evidence from a panel of British and French establishments, INRA-LEA Working Paper 00-06, forthcoming *Quarterly Journal of Economics*.

Cappelli, Peter and Carter, William (2000), Computers, work organization, and wage outcomes, NBER Working Paper 7987, October 2000.

Carayon-Sainfort, Pascale (1992), The use of computers in offices: Impact on task characteristics and worker stress, *International Journal of Human Computer Interaction*, vol. 4, pp. 245-261.

Caselli, Francesco and Coleman II, Wilbur John (2001), Cross-country technology diffusion: The case of computers, NBER Working Paper 8130, February 2001.

Chennells, Lucy and Van Reenen, John (1997), Technical change and earning in British establishments, *Economica*, vol. 64, pp. 587-604.

DiNardo, John and Pischke, Jörn-Steffen (1996), The return to computer use revisited: Have pencils changed the wage structure too?, NBER Working Paper 5606, July 1996.

DiNardo, John and Pischke, Jörn-Steffen (1997), The return to computer use revisited: Have pencils changed the wage structure too?, *Quarterly Journal of Economics*, vol. 112, pp. 291-303.

Doms, Mark, Dunne. Timothy and Troske, Kenneth R. (1997), Workers, wages and technology, *Quarterly Journal of Economics*, vol. 112, pp. 253-290.

Dunne, Timothy, Foster, Lucia, Haltiwanger, John and Troske, Kenneth R. (2000), Wage and productivity dispersion in U.S. manufacturing: The role of computer investment, NBER Working Paper 7465, January 2000.

Dunne, Timothy and Schmitz Jr., James A. (1995), Wage, employment structure and employer-size wage premia: Their relationship to advanced-technology usage at U.S. manufacturing establishments, *Economica*, vol. 62, pp. 89-107.

Entorf, Horst and Kramarz, Francis (1997), Does unmeasured ability explain the higher wages of new technology workers?, *European Economic Review*, vol. 41, pp. 1489-1509.

EITO (2000), *European Information Technology Observatory, Millennium Edition*.

Fernandez, Roberto (2001), Skill-biased technological change and wage inequality: Evidence from a plant retooling, Mimeo, Sloan School of Management, February.

Green, Francis (1999), The value of skills, University of Kent, mimeo July 1999.

Green, Francis and Steve McIntosh (2000), Working on the chain gang? An examination of rising effort levels in Europe in the 1990s, Discussion Paper 465, Centre for Economic Performance, London School of Economics, August 2000, forthcoming *Labour Economics*.

Greenwood, Jeremy and Yorukoglu, Mehmet (1997), 1974, Carnegie Rochester Conference Series on Public Policy, vol. 46, pp. 49-95.

Groot, Loek F.M. and De Grip, Andries (1991), Technological change and skill formation in the bank sector, *Economics of Education Review*, vol. 10, pp. 57-71.

Hamilton, Barton H. (1997), Returns to computer skills and black-white wage differentials, John M. Olin School of Business, mimeo August 1997.

Katz, Lawrence F. (2000), Technological change, computerization, and the wage structure, in *Understanding the Digital Economy; Data, Tools, and Research*, Erik Brynjolfsson and Brian Kahin, eds. (MIT Press, Cambridge MA).

Katz, Lawrence F. and Autor, David H. (1999), Changes in the wage structure and earnings inequality, in *Handbook of Labor Economics*, vol. 3, O. Ashenfelter and D. Card, eds. (Amsterdam: North-Holland).

Katz, Lawrence F. and Murphy, Kevin M. (1992), Changes in relative wages, 1963-1987: Supply and demand factors, *Quarterly Journal of Economics*, vol. 107, pp. 35-78.

Kremer, Michael and Maskin, Eric (1997), Wage inequality and segregation by skill, MIT, mimeo 1997.

Krueger, Alan B. (1993), How computers have changed the wage structure: Evidence from microdata, 1984-1989, *Quarterly Journal of Economics*, vol. 108, pp. 33-60.

Lantz, Ann (1998), Heavy users of electronic mail, *International Journal of Human Computer Interaction*, vol. 10, pp. 361-379.

Levy, Frank and Murnane, Richard J. (1996), With what skills are computers complements?, *American Economic Review Papers and Proceedings*, vol. 86, pp. 258-262.

Lindbeck, Assar and Snower, Dennis J. (2000), Multitask learning and the reorganization of work: From tayloristic to holistic organization, *Journal of Labor Economics*, vol. 18, pp. 353-376.

Lindstroem, Kari (1991), Well-being and computer-mediated work of various occupational groups in banking and insurance, *International Journal of Human Computer Interaction*, vol. 3, pp. 339-361.

Machin, Stephen J. and Van Reenen, John (1998), Technology and changes in skill structure: Evidence from seven OECD countries, *Quarterly Journal of Economics*, vol. 113, pp. 1215-1244.

Miller, Peter W. and Mulvey, Charles (1997), Computer skills and wages, *Australian Economic Papers*, vol. 36, pp. 106-13.

Murphy, Kevin M. and Welch, Finis (2001), Wage differentials in the 1990s: Is the glass half full or half empty? in *The Causes and Consequences of Increasing Inequality*, F. Welch, ed. (Chicago: University of Chicago Press).

Weinberg, Bruce A. (2000), Computer use and the demand for female workers, *Industrial and Labor Relations Review*, vol. 53, pp. 290-308.