

Digital Technology Adoption and Jobs

A Model of Firm Heterogeneity

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Abstract

This paper develops a theoretical framework that expands the task-based models of technical progress and labor markets to allow for firm heterogeneity and wages that vary across firms. The model is compatible with the empirical observation that more productive firms are larger, are more skill intensive, and pay higher wages across skill categories. The model predicts that the decision to invest in information and communications technology depends on firm size and labor market characteristics. As a result of investment in information and communications technology firms grow, become more intensive in complex tasks, become more skilled intensive, and employ more skilled

workers as long as skilled labor is complementary to information and communications technology. Employment of unskilled workers increases as well, provided that firm output growth is sufficiently high to overcome the negative substitution effect. Workers who remain employed are better off because their wage increases with information and communications technology. To the extent that skilled workers have more bargaining power than unskilled workers, or that their wage scheme is more tied to firm performance, wage inequality at the firm level increases with information and communications technology.

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**Digital Technology Adoption and Jobs:
A Model of Firm Heterogeneity¹**

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1. Introduction

The relation between the adoption of digital technologies, its impact on productivity, and the consequences on employment and labor markets has been the subject of much study in the last three decades. Investment in information and communication technologies (ICT) has been credited with the increase in US productivity in the second-half of the 1990s and the increasing productivity gap between the US and the EU. Skill-biased technological change is argued to be one of the main reasons behind the steady increase in the demand for skilled labor, wage inequality and job polarization since the 1980s.

Two main strands of literature have studied the labor market impacts of technological progress: the early literature on skill-biased technological change of Katz and Murphy (1992), Bound and Johnson (1992), Goldin and Katz (1998), among others, and the tasks approach to labor demand of Autor, Levy and Murnane (2003) and Acemoglu and Autor (2011). The literature on skill-biased technological change assumes that technology is complementary with skilled labor, therefore positively affecting the relative demand and wage of skilled workers. The tasks approach argues that the complementarity or substitutability between technology and labor does not occur at the worker category but rather depending on how susceptible different tasks are for automatization. They conclude that tasks performed by workers in the middle of the skill distribution are more likely to be substitutable by machines. Almost all of these papers describe general equilibrium models and use data on wage and employment aggregated up to the district, industry or country level.

Most notably the bulk of the literature in skill-biased technological change and the tasks approach to labor demand features homogeneous firms and competitive labor markets. While these are useful assumptions when studying employment and wages in general equilibrium, the model descriptions miss out on predictions at the firm-level. Firm-level studies have consistently shown that there is high variance in labor force composition and wages across firms. A higher skill share and higher wages are associated with larger, more productive firms that engage in complex activities such as innovation, quality upgrading, and exporting.³ Moreover, the extent to which investing in ICT boosts firm productivity has also been shown to depend on firm characteristics denominated under the umbrella term of organizational capacities.⁴

In this paper we extend the tasks model of Acemoglu and Autor (2011) to allow for firm heterogeneity in technology and non-competitive labor markets with firm-level wages, in order to study the effects of investment in ICT on firm-level outcomes. We start by describing

³ Bernard and Jensen (1999), Verhoogen (2008), Kugler and Verhoogen (2012), Aw et al (2011).

⁴ Machin and Van Reenen (1998), Bloom, Sadun and Van Reenen (2012).

a situation in which firm heterogeneity is Hicks-neutral as in Melitz (2003) and then allow for differences in the relative efficiency with which firms use skilled and unskilled labor. We further allow wages to differ across firms due to rent-sharing as in Amiti and Davis (2011). The product market is monopolistically competitive and thus firms with different price and profit levels co-exist. Firms operate using skilled and unskilled labor, and may additionally use ICT capital. Investing in ICT capital involves paying a fixed adjustment cost given by installation costs, on-the-job training and firing costs. As a result not all firms choose to invest in ICT. As in Acemoglu and Autor (2011), skilled and unskilled labor are perfect substitutes in the production of tasks of different levels of complexity. ICT capital is also a substitute for unskilled labor, whereas the degree of complementarity with skilled labor depends on their elasticity of substitution.

Our model aims to be flexible enough to accommodate several micro-level empirical facts. Namely, that firms make different decisions. They differ in size, in the skill ratio, in wages, and on whether they invest or not in ICT. It also allows for wage differences across workers that are otherwise alike except for which firm they work for. Our model predicts that as a result of ICT firms grow, pay higher wages, become specialized in more complex tasks, and employ more skilled workers and become more skilled intensive as long as skilled labor and ICT are complements. Employment of unskilled workers increases, though not as much as employment of skilled workers, if firm output growth due to ICT investment is sufficiently high to overcome the negative substitution effect. It also predicts that workers that remain employed at the original firm experience an increase in wage.

The model is of partial equilibrium in the sense that we consider one industry and fixed wages, and that we do not model firm entry. Our model is static, however, we loosely interpret predictions of scenarios with and without ICT as changes in firm behavior due to adoption of ICT.

The paper is organized as follows. Section 2 describes the background literature on the impact of technological progress on labor outcomes and productivity. Section 3 discusses the model of firm heterogeneity. Section 4 concludes.

2. Background

In this section we briefly review the literature on technology adoption and its impact on labor markets, including the early literature of skill-biased technological change as well as the more recent tasks approach to the demand for skills. We end with a discussion of the impact of investment in ICT on productivity.

Skilled-biased technological change

The rise in the skill premium, and especially the college premium, during the 1980s and 1990s motivated a large literature that pointed towards skill-biased technological change as a driving force behind this phenomenon.⁵ Several early papers such as Katz and Murphy (1992), Bound and Johnson (1992), and Berman, Bound and Griliches (1994) show that the college premium grew significantly in the US during the 1980s (Berman et al, 1994, estimate the increase in the college premium in 10 percentage points). They argue that while the supply of college graduates did not grow as fast during the 1980s as it did during the 1970s, it still grew significantly. To account for the rise in the skill premium substantial growth in the demand for skills must have taken place. Berman, Bound and Machin (1998) find similar results for OECD countries.

Katz and Murphy (1992), Card and Lemieux (2001), Autor, Katz and Krueger (1998), among others, use a demand and supply framework in which the demand for skilled and unskilled labor is based on a production function that allows for factor augmenting technological progress. The output production function takes the form

$$x_t = [\alpha_t(a_t L_t)^\rho + (1 - \alpha_t)(b_t H_t)^\rho]^{1/\rho}$$

where x_t is output and H_t and L_t are skilled and unskilled labor. The time-varying parameters a_t and b_t are factor augmenting technological change. Based on an assumption of inelastic short-run supply and competitive labor markets, Katz and Murphy (1992) derive an estimable equation linking the skill premium to the relative supply of skills and a trend representing skill augmenting technological change. They estimate the increase in the demand for skills to be of 3.3 percent annually. Card and Lemieux (2001b) find that it is relevant to define the supply of skills by age cohort, as workers of different age and experience are not interchangeable.

Krusell et al (2000) Interpret skill-biased technological change as a complementarity between capital and skilled labor. They argue that skill-biased technological change is treated in previous papers as a latent unobserved variable. They instead work with a production function in which capital is introduced explicitly as complementary to skilled workers. The function takes the form

$$x_t = A_t [\mu L_t^\sigma + (1 - \mu)(\lambda K_t^\rho + (1 - \lambda)H_t^\rho)^{\sigma/\rho}]^{(1-\alpha)/\sigma}$$

where x_t is output, H_t and L_t are skilled and unskilled labor, and K_t is capital. The complementarity between capital and skilled labor is modeled with a smaller elasticity of

⁵ De-unionization, International trade, and more recently offshoring of manufacturing jobs have been pointed out as alleged culprits as well.

substitution than between capital and unskilled labor ($\rho < \sigma$). They use national accounts data to build a time series of infrastructure and capital equipment from 1962 to 1993 and data on labor supply from CPS surveys. Their estimates are consistent with capital skill complementarity. Additionally, they find that capital grew more rapidly after 1975, when the skill premium started to rise more sharply. Their results indicate that after accounting for the capital-skill complementarity most of the changes in skill premium become accounted for.

Goldin and Katz (1998) study the complementarity of capital and skilled labor from a historical perspective using US Census of Manufacturers for 1909, 1919, 1929, and the NBER Manufacturing Productivity Database for later time periods. They argue that the complementarity between capital and skills is not a recent phenomenon and that it goes back to the beginning of their sample period.

More specifically related to the use of digital technology, Krueger (1993) finds that workers who use computers at work earn a wage premium of 10% to 15% and estimates that about one-third of the rise in skill premium is due to increased computer use. DiNardo and Pischke (1997), however, cast doubt on these findings by estimating substantial wage returns to the use of pencils, telephones, and working in a sitting position as well. Autor, Katz and Krueger (1998) use CPS data sets to assess how on-the-job computer usage varies across industries and argue that the rise in the demand for skills is actually increased demand for computing skills.

The tasks approach

Autor, Levy and Murnane (2003) introduce a tasks approach to labor demand. The tasks approach emphasizes the role of automatization of tasks in relation to technological progress and labor markets. Autor et al (2003) state that computers can substitute workers who perform cognitive and manual tasks that can be accomplished by following an explicit set of rules (routine tasks), while computers complement workers performing non-routine and problem-solving and complex tasks. They model these ideas with a production function that takes the form

$$x_t = (L_R + C)^{1-\beta} L_N^\beta$$

where L_R and L_N are routine and non-routine workers and C are computers. Computers are perfect substitutes for routine labor and have a declining price. They use data on information on the task composition of jobs from 1960 to 1998 and find that computer usage is linked to a reduction of employment in routine tasks and with an increase in demand for college graduates.

A following strand of literature argues that the patterns of wage inequality and the demand for skills have been shifting since the 1990s towards an increase in polarization (i.e.

a fall in demand for middle-skill workers). Autor, Katz and Kearney (2008) find that wage inequality at the bottom half of the income distribution has not increased since the 1980s and that, instead, wage inequality has risen in the upper tail. Goos and Manning (2007) and Goos, Manning and Salomon (2014) show that there has been a decrease in the share of middle-skill occupations in total employment in the UK and in 16 European countries. The unifying idea behind these findings is based on the tasks approach: occupations in the middle of the skill distribution are more susceptible to automatization than occupations at the lower and upper tails.

Acemoglu and Autor (2011) develop a more sophisticated model of the task content of jobs in which output is produced by a continuum of tasks and where each task can be performed by low, medium or high-skill workers, or by technology. Their model can account for job polarization, as tasks performed by middle-skill workers are subject to be substituted by technology. This is the mechanism that drives the concentration in high and low pay occupations. The model that we develop in Section 3 is loosely based on Acemoglu and Autor (2011).

Autor and Dorn (2013) study the impact of computerization on the demand for low-skilled labor. They use district-level data for the US and show that areas with high levels of routine tasks have experienced greater adoption of ICT, greater reallocation of workers from routine tasks to the service sector, wage polarization, and large inflows of high and low skilled workers.

Michaels et al (2014) study whether ICT has contributed to the rise in polarization. They put together a comprehensive industry-level data set on 11 advanced countries from 1980 to 2004. Their findings indicate that the industries which invested more heavily in ICT demanded more highly qualified workers in detriment of workers with intermediate education. Additionally, the estimated effect is quantitatively large, and can explain one-quarter of the college wage bill in the economy as a whole.

The firm-level evidence on skilled-biased technological change, occupations and tasks, and labor outcomes is scarce. One example is Akerman et al (2014). They study skill complementarity of broadband internet in Norway and show that access to broadband internet improves the labor market outcomes and the productivity of skilled workers.

Labor market institutions

To the extent that digital technology is a substitute for certain types of workers or tasks, investment in ICT is associated with employment reallocation. Employment protection laws that make labor adjustment costly, such as firing costs, are expected to negatively affect the adoption of ICT. This effect is larger the larger the substitutability between ICT and certain types of workers.

Gust and Marquez (2004) present empirical evidence that across industrialized countries there is a negative correlation between ICT investment and employment protection laws. They develop a dynamic model of vintage capital and skilled-biased technological change. In each period a firm decides whether to upgrade technology, which in turn requires to upskill the labor force. Firing costs delay or prevent firm decisions to adopt the latest technology.

Employment protection legislation can also be viewed as discouraging to undertaking risky activities such as investment in innovation and in ICT-intensive sectors, as in Bartelsman, Gautier and de Wind (2016), Saint Paul (2002), Koeniger (2005), Bartelsman and Hinloopen (2005), and Samainego (2006). Bartelsman et al (2016) argue that, because of the experimentation and changes required in organizational structure, the outcome of investment in ICT is highly uncertain. This is supported by the empirical finding that productivity is more dispersed in ICT-intensive sectors (Brynjolfsson et al., 2008). If for a given firm investment in ICT is unsuccessful, the firm might be forced to exit the market because it cannot break even. Thus, incentives to invest in ICT depend on exit costs, with higher exit costs being detrimental to investment in ICT. In this scenario, firing costs are a barrier to investment in ICT.⁶

Using a cross-industry and cross-country panel dataset of the US and the EU (EUKLEMS), Bartelsman et al (2016) show that high-risk ICT-intensive sectors are smaller in terms of employment in countries with stricter labor regulations. These empirical facts hold when comparing the EU to the US, where labor regulations are more flexible, and when comparing countries within the EU. Further, the effect of labor regulations is increasing in the risk of the investment. The paper also develops and calibrates a model and their simulations show that, due to lower investment in ICT, aggregate productivity in the US would be 10 percent lower if severance payments in the US were similar to the average cost in Europe.

Digital technology adoption and productivity

Empirical studies find that ICT is important in explaining productivity differences across countries, across sectors, and across firms. Treating ICT as an input that enters into the production function, a large group of papers has focused on studying the role of ICT in the resurgence in labor productivity in the US during the 1990s, from the growth accounting and cross-industry econometric perspectives. Jorgenson, Ho and Stiroh (2008) and Oliner, Sichel and Stiroh (2007) argue that the ICT producing sectors have been responsible for the increase in productivity from 1995 to 2000, whereas after 2000 further growth in investment

⁶ Acharya, Baghai and Subramanian (2013) make the opposite argument that stricter labor laws work as a commitment device by preventing firms from dismissing workers after short-run failures and thus encouraging employees to engage in risky innovative activities that are profit maximizing in the long-run.

in ICT has not occurred in ICT producing sectors but rather in ICT using sectors. In contrast, both investment in ICT and productivity improvements have been much more moderate in the EU during the same period (von Ark et al, 2008). For comprehensive surveys see Draca, Sadun and Van Reenen (2007) and Syverson (2011).

Firm level studies are scarcer, partly due to the endogeneity in input choice that arises in the estimation of production function, and also due to the difficulty in measuring ICT capital at the firm level. In particular, one potential problem is that the direct cost of purchase of ICT does not fully represent the cost of adjusting the organization of the firm to deal with the new technology. To address this issue several firm level studies have highlighted the complementarities between ICT, organizational capacities, and human capital. Bresnahan, Brynjolfsson and Hitt (2002) run their own survey and find that ICT is complementary to decentralized decision making, self-managing teams, worker autonomy, broader responsibilities of workers, and skills. They attribute part of the large estimated returns to ICT to be derived from the change in organizational capacities. Further support for the organizational capacities hypothesis is provided by Brynjolfsson and Hitt (2003). They study investment in computers and find that the explanatory power of computers on firm output growth is substantially larger in the medium run than in the shorter run, suggesting that ICT capital becomes more productive as firms have time to adjust their labor force, managerial practices, and overall firm capabilities.

Bloom, Draca and Van Reenen (2016) apply the organizational capacities hypothesis to explain the differences in the contribution of ICT to productivity growth between the US and Europe. Using a panel of firms they show that US multinationals operating in Europe obtain larger productivity gains from ICT compared to European firms. They further find evidence that the productivity advantage of ICT in US firms is due primarily to different management practices.

3. Model

In this section we describe a partial equilibrium model of firm heterogeneity and investment in ICT. We start describing a situation in which firms produce using skilled and unskilled labor. We then allow for investment in ICT. The model is based on the task production function of Acemoglu and Autor (2011), extended to allow for firm heterogeneity as in Melitz (2003) and rent-sharing wage schedules as in Amiti and Davis (2011).

Products and preferences

In a given industry there is a continuum of product varieties, each variety indexed by v , with the total mass of varieties given by V . Varieties are horizontally differentiated and enter

symmetrically into the utility function of consumers. The utility function is of CES type and is given by

$$u = \left[\int_{v \in V} x(v)^{\frac{\varepsilon-1}{\varepsilon}} dv \right]^{\frac{\varepsilon}{\varepsilon-1}}$$

where $x(v)$ is the quantity of variety v and ε is the elasticity of substitution across varieties. All consumers have the same preferences. The total expenditure in the industry is E . Under these assumptions, the aggregate demand function is

$$x(v) = \left(\frac{p(v)}{P} \right)^{-\varepsilon} \frac{E}{P}$$

where $p(v)$ is the price of variety v and P is the CES price defined as

$$P = \left[\int_{v \in V} p(v)^{1-\varepsilon} dv \right]^{\frac{1}{1-\varepsilon}}$$

Firms and technology of production

Each differentiated variety is produced by a single product firm under economies of scale as in Melitz (2003). Firms differ in their technology of production. The heterogeneity across firms is summarized by a technology parameter θ . Upon entry, firms take a draw of the parameter θ from a known distribution G . Firms that choose to remain in the market and produce, pay a fixed cost of production F . Firms that cannot break even because variable profits are not large enough to cover the fixed cost, exit the market. The mass of product varieties V is the mass of firms that choose to remain in the market in equilibrium.

The production process has a two-tier structure. In the upper tier, production of final good x is carried out by a combination of tasks $t(i)$ indexed by $i \in [0,1]$ as in Acemoglu and Autor (2011). The different tasks correspond to different stages of the actual production process, prior stages such as design and development, as well as other firm activities such as management, commercialization, and distribution. The aggregation of tasks into final output takes a Cobb-Douglas form given by

$$x(\theta) = \theta \exp \left[\int_0^1 \ln t(i) di \right].$$

Notice that this is a flexible form that allows firms to choose different quantities of each task. The firm heterogeneity parameter θ enters the production function multiplicatively. A higher θ corresponds to higher output per unit of the Cobb-Douglas composite of tasks. We write

output $x(\theta)$ as a function of the productivity parameter θ in order to highlight that firm-level variables vary with firm-level productivity.

In the lower tier we have the production of each task, given by

$$t(i, \theta) = a_L(i, \theta) L(i, \theta) + a_H(i, \theta) H(i, \theta).$$

The parameters $a_H(i, \theta)$ and $a_L(i, \theta)$ are the inverse unit requirements of skilled and unskilled workers needed to produce one unit of task i , which vary across firms with θ . The variables $H(i, \theta)$ and $L(i, \theta)$ are the number of skilled and unskilled workers applied to the production of task i . For convenience, we sort tasks so that the ratio of inverse unit requirements $a_H(i, \theta)/a_L(i, \theta)$ is increasing in the task index i . As the task index increases, tasks become more complex and the comparative advantage of skilled workers increases. We further assume that the ratio of inverse unit requirements is continuously differentiable.

The production of tasks is Ricardian, in the sense that in equilibrium each task is carried out either by skilled (H) or unskilled workers (L) as the two types of workers are perfect substitutes, albeit with different productivities and wages. We return to the optimal combination of skilled and unskilled workers after discussing labor markets. The marginal cost varies across firms with θ .

Labor markets

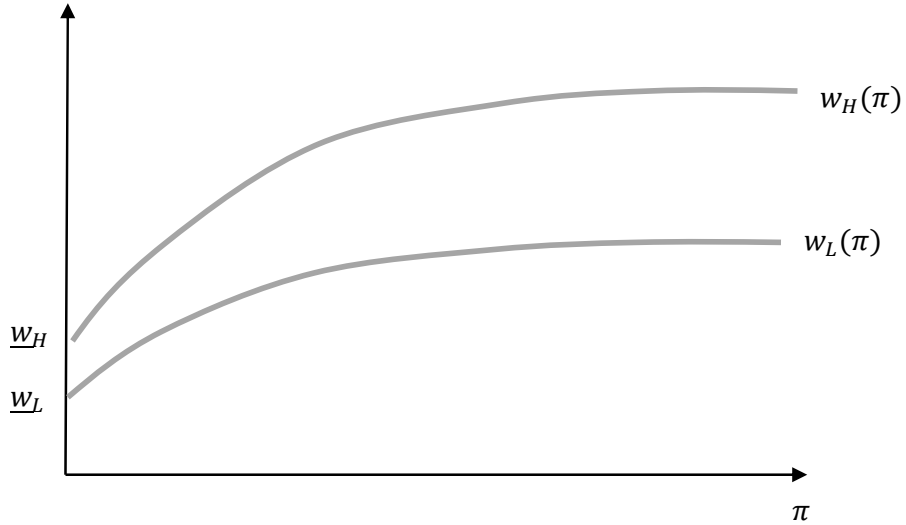
We assume that labor markets are not competitive and that wages vary by firm due to rent-sharing. Let π denote firm profits. Firm-level wages for skilled and unskilled workers follow rent-sharing schedules given by $w_H(\pi)$ and $w_L(\pi)$, both increasing in π , and with $w_H(\pi) > w_L(\pi)$, $\forall \pi$. (Figure 1)

Wages are increasing in profits because workers have fair-wage demands. The wage schedules are a reduced form that can result from an efficiency wages model where workers only exert effort if they perceive their wage is fair, or as the results of a bargaining solution after job search. Together with firm heterogeneity, the fair-wage schedules produce wages that vary by firm, as in Egger and Kreickmeier (2009), Amiti and Davis (2011), and Helpman, Itskhoki, and Redding (2010). Our assumptions imply that within a firm, skilled workers are paid more than unskilled workers, and that workers of the same type are paid the same wage across tasks.

Similarly to Amiti and Davis (2011), we define a lower bound for wages based on firms that make zero profits, given by $\underline{w}_H = w_H(0)$ and $\underline{w}_L = w_L(0)$, and we assume that there are upper bounds given by \bar{w}_H and \bar{w}_L , so that $\lim_{\pi \rightarrow \infty} w_H(\pi) = \bar{w}_H$ and $\lim_{\pi \rightarrow \infty} w_L(\pi) = \bar{w}_L$. We further assume that the rent-sharing schedules increase at the same rate for skilled and

unskilled workers, so that the relative wage is the same for all firms. This could arise in a situation in which skilled and unskilled workers have the same bargaining power (relative to

Figure 1. Fair-Wage Schedules



The curves $w_H(\pi)$ and $w_L(\pi)$ are the rent-sharing wage schedules of skilled and unskilled workers. They depend on firm profits π .

different outside options) or in a situation in which wage increases are only perceived as fair if they are proportionally the same across skill groups. The implication is that $\frac{w_H}{w_L} = \frac{w_H(\pi)}{w_L(\pi)} = \frac{\bar{w}_H}{\bar{w}_L}, \forall \theta$. We later relax this assumption. Without loss of generality, we write the relative wages as $\frac{w_H}{w_L}$. To guarantee an interior solution for both types of labor, which is the interesting case to study, we assume that

$$\frac{a_H(0, \theta)}{a_L(0, \theta)} < \frac{w_H}{w_L} < \frac{a_H(1, \theta)}{a_L(1, \theta)}, \forall \theta.$$

Cost function, labor demands and production of tasks

Firms demand skilled and unskilled labor based on the task-specific inverse labor requirements $a_H(i, \theta)$ and $a_L(i, \theta)$, and based on wages $w_H(\pi)$ and $w_L(\pi)$. Since profits vary across firms through firm differences in the technology parameter, we write the wage schedules as functions $w_H(\theta)$ and $w_L(\theta)$. To find the labor demands, production of tasks, and the variable unit cost function we need to solve a cost minimization problem backwards.

First firms allocate skilled and unskilled workers to tasks, and then they combine tasks optimally to produce one unit output.

Firms choose to produce each task i with either skilled or unskilled labor according to which option is less costly. The cost of task i is $\frac{w_L(\theta)}{a_L(i,\theta)}$ when it is produced with unskilled labor and $\frac{w_H(\theta)}{a_H(i,\theta)}$ when it is produced with skilled labor. As in Acemoglu and Autor (2011), because the ratio $a_H(i,\theta)/a_L(i,\theta)$ is increasing in the task index i , there is a unique value $i^*(\theta) \in (0,1)$ such that the less complex tasks $i < i^*(\theta)$ are carried out by unskilled workers, and the more complex tasks $i \geq i^*(\theta)$ are carried out by skilled workers. The condition that defines i^* is

$$\frac{w_L(\theta)}{a_L(i^*(\theta),\theta)} = \frac{w_H(\theta)}{a_H(i^*(\theta),\theta)}.$$

The equilibrium assignment of workers to tasks is depicted in Figure 2.

In turn, the optimal combination of tasks depends on the cost of each task, given by $\frac{w_L(\theta)}{a_L(i,\theta)}$ or $\frac{w_H(\theta)}{a_H(i,\theta)}$ depending on which type of labor is employed in the production of that task.

We denote the unit variable cost with $c(\theta)$. The production of tasks is given by

$$t(i,\theta) = \begin{cases} \frac{a_L(i,\theta)}{w_L(\theta)} c(\theta) x(\theta) & \text{if } i < i^*(\theta) \\ \frac{a_H(i,\theta)}{w_H(\theta)} c(\theta) x(\theta) & \text{if } i \geq i^*(\theta). \end{cases}$$

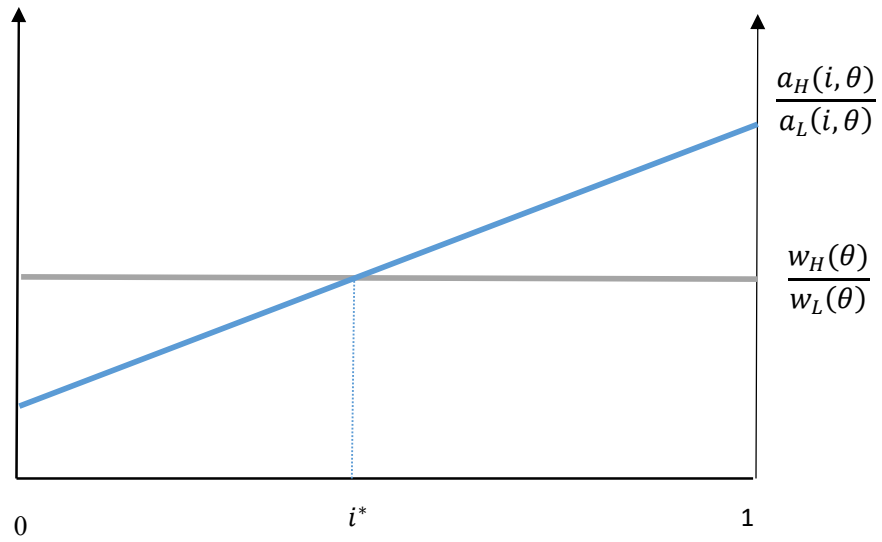
Figure 3 depicts an example with two tasks, j and i , where the first task is produced with skilled labor and the second task is produced with unskilled labor. Increases in the wage of unskilled labor or in the unit requirements of unskilled labor for task i imply an increase in the production of the task j , that uses skilled labor, and vice versa.

Given the Cobb-Douglas combination of tasks of the upper-tier production function, the unit variable cost is a Cobb-Douglas index of the cost of producing each task. For less complex tasks ($i < i^*(\theta)$), the cost of the task depends on the unit requirements and wage of unskilled workers, whereas for more complex tasks ($i \geq i^*(\theta)$), the cost depends on the unit requirements and wage of skilled workers. The unit variable cost is

$$c(\theta) = \frac{1}{\theta} \exp \left[\int_0^{i^*(\theta)} \ln \frac{w_L(\theta)}{a_L(i,\theta)} di + \int_{i^*(\theta)}^1 \ln \frac{w_H(\theta)}{a_H(i,\theta)} di \right],$$

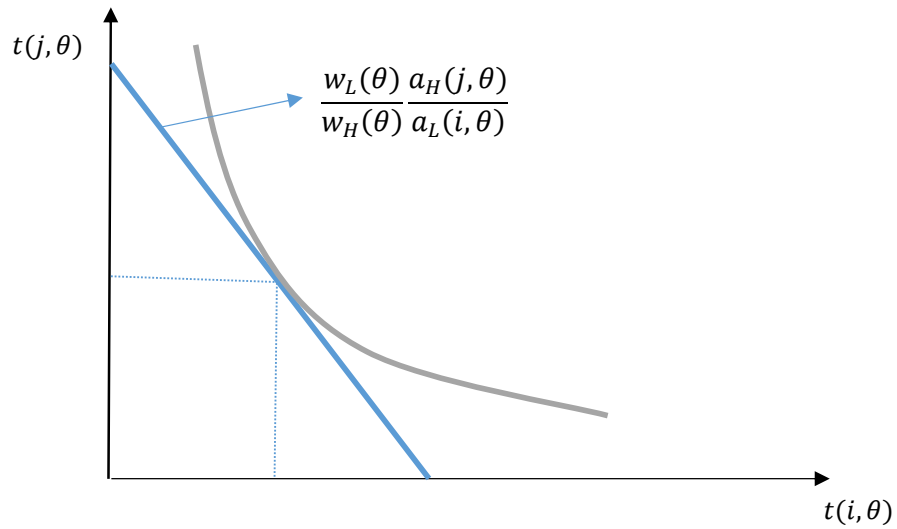
The cost function depends negatively on θ through the multiplicative productivity term and through the inverse unit requirements a_H and a_L , and depends positively on θ through wages, due to rent sharing. The net effect of θ on costs is negative, as rent-sharing works

Figure 2. Assignment of Skilled and Unskilled Workers to Tasks



Tasks to the left of i^* are performed by unskilled workers (L), whereas tasks to the right of i^* are performed by skilled workers (H).

Figure 3. Combination of tasks



The graph represents a situation in which task i , on the horizontal axis, is performed by unskilled workers and task j , on the vertical axis, is performed by skilled workers.

through higher profits and higher profits are in turn derived from lower costs. Therefore, $c(\theta)$ is decreasing in θ .

To obtain the demand for skilled and unskilled labor we use the input requirements for each task, the production of tasks, and we integrate over the tasks that utilize each type of worker. Total firm demand for skilled and unskilled workers is

$$H(\theta) = \frac{1 - i^*(\theta)}{w_H(\theta)} c(\theta)x(\theta),$$

$$L(\theta) = \frac{i^*(\theta)}{w_L(\theta)} c(\theta)x(\theta).$$

Given that there are constant returns to scale in the variable factors (that is, ignoring the fixed costs), the ratio of skilled to unskilled workers is constant for all production levels. It is given by

$$\frac{H(\theta)}{L(\theta)} = \frac{w_L(\theta)}{w_H(\theta)} \frac{1 - i^*(\theta)}{i^*(\theta)}.$$

The ratio of skilled to unskilled workers depends on the cutoff $i^*(\theta)$, which depends on unit requirements and wages, as the cutoff dictates which type of worker is applied to each task. It further depends on the relative wage, as both the cutoffs and relative wage determine the quantity of each task that is carried out and combined into final product output.

Profit maximization

The output market is monopolistically competitive. Firms are small relative to the market and they choose prices to maximize profits subject to their demand function and taking the price index as given. The firm's objective function is

$$\pi(\theta) = \max_{p(\theta)} (p(\theta) - c(\theta)) x(p(\theta)) - F.$$

The equilibrium price follows the usual CES pricing rule

$$p(\theta) = \frac{\varepsilon}{\varepsilon - 1} c(\theta).$$

Indirect profits are given by

$$\pi(\theta) = A c(\theta)^{(1-\varepsilon)} - F$$

with $= \varepsilon^{-\varepsilon} (\varepsilon - 1)^{(\varepsilon-1)} E$. Given that the variable unit cost is decreasing in θ , prices are decreasing in θ and profits are increasing in θ . Mark-ups are constant in quantity and the

same across firms. Firms produce if indirect profits (net of fixed costs) are zero or strictly positive. Firms that do not break even exit the market.

Notice that due to the rent-sharing wage schedules, the variable unit cost $c(\theta)$ depends on profits. Solving the firm profit maximization problem involves finding an equilibrium in which maximized profits predict a given marginal cost through the rent-sharing constraints, and that same marginal cost generates the same level of maximized profits when the CES pricing rule is applied. As shown by Amiti and Davis (2011), because for a given θ the dependence of costs on profits is monotonically increasing, the CES pricing rule holds.⁷ This is also a property of Nash bargaining solutions.

The role of firm heterogeneity

The firm heterogeneity parameter θ affects firm decisions of price, relative labor demands, and wages. There are two different channels through which the heterogeneity parameter operates: it enters the upper-tier Cobb-Douglas production function multiplicatively, and it affects the inverse labor requirements in the lower-tier production function. In what follows we describe the role of each channel separately.

We start by considering a situation in which technology differences (captured by θ) do not affect the ratio of inverse input requirements. The objective of this exercise is to describe a scenario in which the only channel of technological firm heterogeneity is the Hicks-neutral multiplicative component of the upper-tier production function, as in Melitz (2003), and in which wages vary by firm as in Amiti and Davis (2011).

Proposition 1. *Productivity, size and wages.*

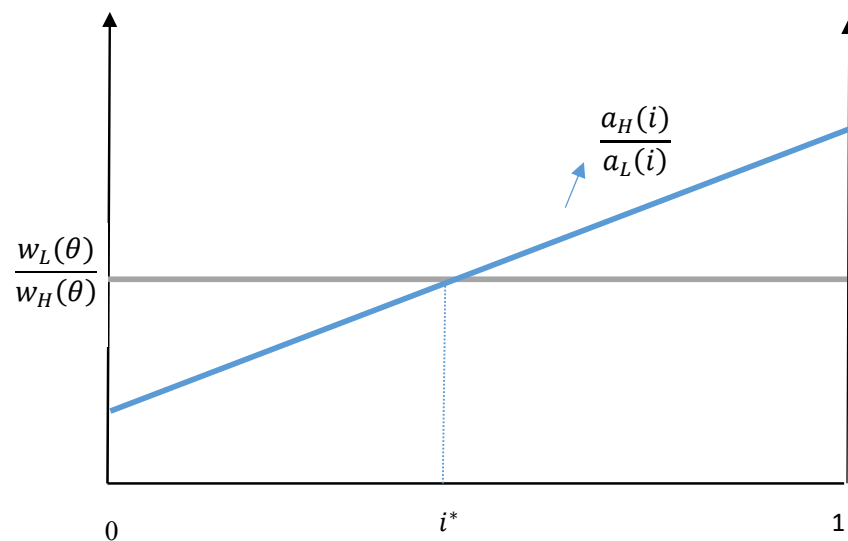
Assume that $\frac{a_H(i,\theta)}{a_L(i,\theta)} = \frac{a_H(i)}{a_L(i)} \forall i$, then,

- (i) $x(\theta), w_H(\theta), w_L(\theta)$ are increasing in θ ;
- (ii) $i^*(\theta_0) = i^*(\theta_1), \forall \theta_0, \theta_1$;
- (iii) $\frac{H(\theta_0)}{L(\theta_0)} = \frac{H(\theta_1)}{L(\theta_1)}, \forall \theta_0, \theta_1$.

Because the relative efficiency and the relative cost of skilled to unskilled labor are the same across firms, the assignment of each type of worker to tasks is also the same (Figure 4), as is the relative production of tasks (Figure 5), and total relative labor demand. Firm heterogeneity only predicts differences in scale and in wages across firms. The scale of firms both in terms of units of production and skilled and unskilled employment depends

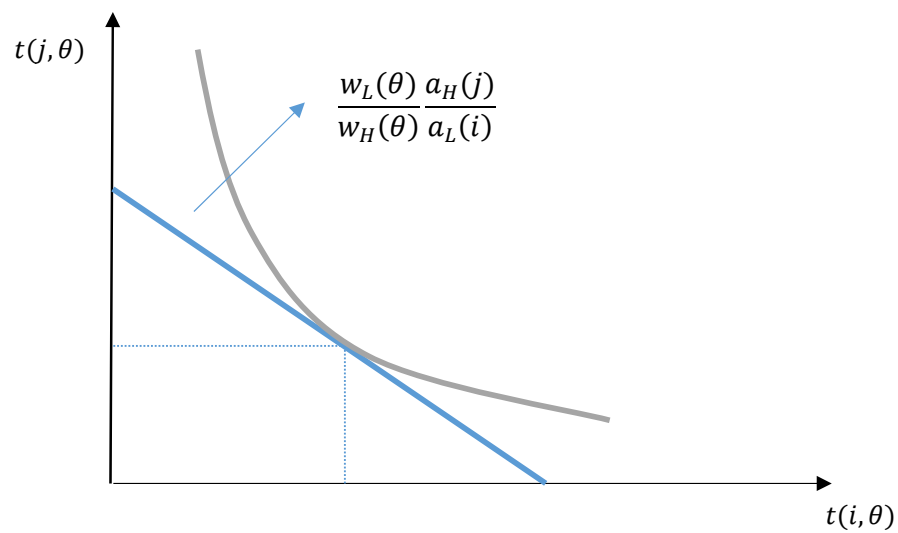
⁷ Costs are increasing in wages, which in turn are increasing in profits.

**Figure 4. Assignment of Skilled and Unskilled Workers to Tasks
Technology Differences are Hicks-Neutral**



The assignment of tasks to workers is the same across firms with different θ .

**Figure 5. Combination of tasks
Technology Differences are Hicks-Neutral**



The combination of tasks is the same across firms with different θ .

positively on the Hicks-neutral productivity θ . Scale differences across firms unfold from $c(\theta)$ and therefore $p(\theta)$ being decreasing in θ . The cross sectional prediction is that more productive firms are larger and pay higher wages, and that skill intensity is the same across firms.

We now turn to a situation in which there is a complementarity between total factor productivity and skilled labor, modeled as differences in Hicks-neutral productivity as well as input requirements across firms. The objective of this scenario is to study conditions under which the ratio of skilled to unskilled workers varies across firms.

Proposition 2. *Complementarity between productivity and skilled labor.*

Assume that $\frac{a_H(i,\theta)}{a_L(i,\theta)}$ is increasing in θ , then,

- (i) $x(\theta), w_H(\theta), w_L(\theta)$ are increasing in θ ;
- (ii) $i^*(\theta)$ is decreasing in θ ;
- (iii) $\frac{H(\theta)}{L(\theta)}$ is increasing in θ .

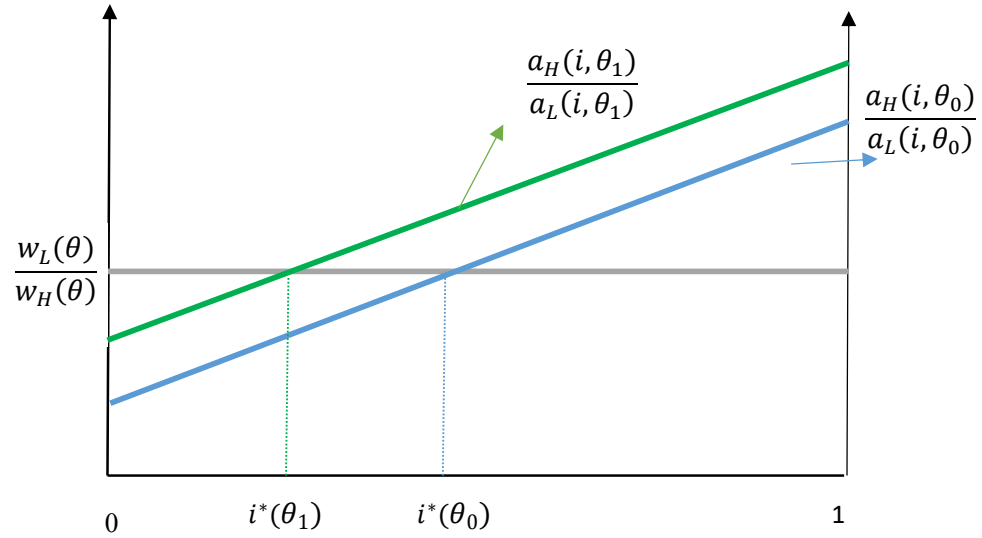
Intuitively, differences in technology that are not Hicks-neutral generate differences in relative factor demands. The situation is depicted in Figures 6 and 7. In Figure 6, the inverse relative input requirements of the more efficient firm (green line) lie above the inverse relative input requirements of the less efficient firm (blue line). As a result, the more productive firms allocate a larger number of tasks to skilled workers. In Figure 7, the more efficient firm faces lower relative costs for skilled tasks (green line) compared to the less efficient firm (blue line). The most efficient firm is more intensive in skilled tasks per unit of output. The cross sectional prediction of this scenario is that more productive firms are larger, pay higher wages, and are more skill intensive. All firms pay the same relative wage.

Investment in ICT

We now assume that firms have the option to invest in ICT. We denote the stock of ICT with T . Each unit of T has a unit cost of w_{ICT} . A positive investment in ICT also implies paying a fixed cost Ψ . The fixed cost represents the adjustment costs of adopting the new technology, given by the installation of the new technology itself, training of the labor force, and firing costs of displaced workers. Because of the fixed cost, not all firms invest in ICT in equilibrium.

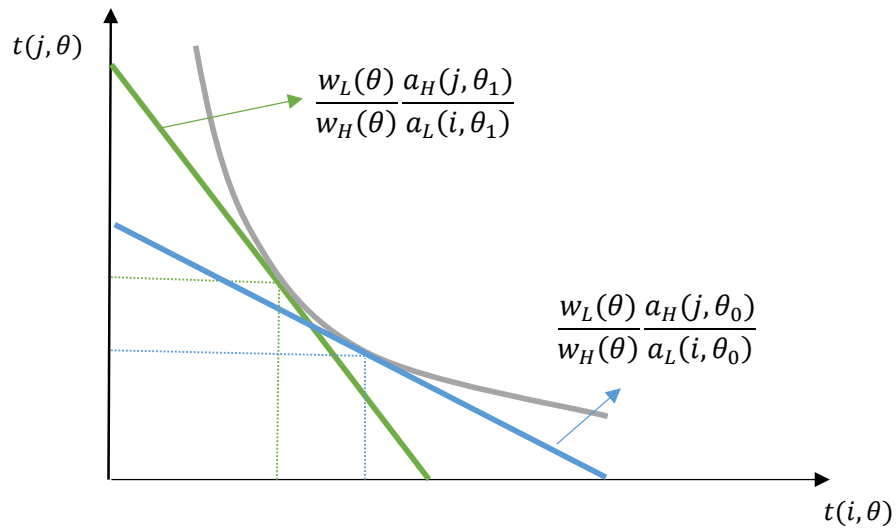
ICT capital is applied to tasks in the same manner as skilled and unskilled labor, with the caveat that it is combined with skilled labor. The upper-tier production function remains unchanged, as output is obtained with the same combination of tasks as without ICT. The

**Figure 6. Assignment of Skilled and Unskilled Workers to Tasks
Varying Relative Efficiency of Skilled and Unskilled Labor**



The graph compares a more efficient firm (θ_1 , in green) with a less efficient firm (θ_0 , in blue). The more efficient firm assigns skilled workers to a larger set of tasks.

**Figure 7. Combination of tasks
Varying Relative Efficiency of Skilled and Unskilled Labor**



The graph compares a more efficient firm (θ_1 , in green) with a less efficient firm (θ_0 , in blue), and a more complex task (j , in the vertical axis) with a less complex task (i , in the horizontal axis). The more efficient firm is more intensive in complex tasks.

possibility to invest in ICT therefore affects the lower-tier production function, which for strictly positive levels of T is given by

$$t^T(i, \theta) = a_L(i, \theta) L(i, \theta) + a_H(i, \theta) \left[H(i, \theta)^{\frac{\sigma-1}{\sigma}} + T(i, \theta)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad \sigma > 1.$$

The functional form of the lower-tier production function reflects the idea that ICT can replace workers in some tasks but that it also needs workers to function. Each task is performed by either unskilled workers, or a CES combination of skilled workers and ICT capital where σ is the elasticity of substitution. Unskilled labor and the combination of skilled labor and ICT capital are perfect substitutes, whereas the substitutability of skilled workers and ICT capital is dictated by σ . The CES combination also allows for the extreme case in which skilled workers and ICT are perfect substitutes ($\sigma \rightarrow \infty$). To keep the model tractable we assume that there are no technological advantages of ICT in the inverse input requirements, $a_L(i, \theta)$ and $a_H(i, \theta)$. The latter refers to the contribution of the composite of skilled labor and ICT to the production of task i .

We define the cost of a combined unit of skilled labor and ICT as a CES index given by

$$s^T(\theta) = (w_H^T(\theta)^{1-\sigma} + w_{ICT}^{1-\sigma})^{1/(1-\sigma)},$$

where $w_H^T(\theta)$ is the rent-sharing schedule for skilled workers when the firm chooses to invest in ICT. In what follows we denote all variables that are different in the ICT scenario with a subscript T . Because the elasticity of substitution is greater than one, the price index $s^T(\theta)$ is smaller than both the skilled wage $w_H^T(\theta)$ and the price of one unit of ICT capital w_{ICT} . The advantage of investing in ICT are the savings in costs implied by the convexity of the technology that combines skilled workers and ICT capital. In the limit, as ($\sigma \rightarrow 1$) the price index tends to zero as the input combination becomes more convex; whereas as ($\sigma \rightarrow \infty$) the index converges to the price of the input with the lowest cost as only that input is used in the production of complex tasks. In other words, $s^T(\theta)$ is never higher than the minimum between $w_H^T(\theta)$ and w_{ICT} , and unless ($\sigma \rightarrow \infty$) it is lower than both.

The allocation of inputs to tasks, and of tasks to output is analogous to the case without ICT. We briefly review the main results. The cutoff task $i^{*T}(\theta)$ is defined by

$$\frac{w_L^T(\theta)}{a_L(i^{*T}(\theta), \theta)} = \frac{s^T(\theta)}{a_H(i^{*T}(\theta), \theta)}.$$

The wage of unskilled workers is affected by the investment in ICT through the rent-sharing schedule. The production of tasks is given by

$$t(i, \theta) = \begin{cases} \frac{a_L(i, \theta)}{w_L^T(\theta)} c^T(\theta) x^T(\theta) & \text{if } i < i^{*T}(\theta) \\ \frac{a_H(i, \theta)}{s^T(\theta)} c^T(\theta) x^T(\theta) & \text{if } i \geq i^{*T}(\theta). \end{cases}$$

The unit variable cost is

$$c^T(\theta) = \frac{1}{\theta} \exp \left[\int_0^{i^{*T}(\theta)} \frac{w_L^T(\theta)}{a_L(i, \theta)} di + \int_{i^{*T}(\theta)}^1 \ln \frac{s^T(\theta)}{a_H(i, \theta)} di \right].$$

The unit variable cost is a combination of the wage of unskilled workers and the index that combines the wages of skilled workers and the price of ICT. For all firms, the unit variable cost with ICT is lower than with no ICT, $c^T(\theta) < c(\theta), \forall \theta$. To discuss this more formally notice that there are three key differences between $c^T(\theta)$ and $c(\theta)$. The first difference is the cost of the complex tasks, given by $(s^T(\theta) - w_H(\theta))$, which we can decompose as $(s^T(\theta) - w_H^T(\theta)) - (w_H(\theta) - w_H^T(\theta))$; the second difference is the unskilled wage $(w_L^T(\theta) - w_L(\theta))$; and the third difference is the change in the cutoff task from $i^*(\theta)$ to $i^{*T}(\theta)$. As we discussed above, the combined CES index $s^T(\theta)$ is lower than the skilled wage $w_H^T(\theta)$; this is the driving force behind the savings in variable costs. In the case that profits go up with ICT, the skilled and unskilled wages go up as well, $w_H(\theta) - w_H^T(\theta) < 0$ and $w_L(\theta) - w_L^T(\theta) < 0$. The increase in wages works against the reduction in variable costs. Notice however that the increase in wages, by definition of the fair-wage schedules, only occurs if profits increase, which in turn only occurs if variable costs indeed decrease. Finally, the change in the cutoff task $i^*(\theta)$ is an endogenous firm decision and can only be cost saving. A further implication is that $s^T(\theta) - w_H(\theta) < 0$.

Despite the reduction in variable costs, not all firms invest in ICT because of the fixed cost Ψ . In order to decide whether to pay the fixed cost Ψ , firms compare profits with and without investment in ICT net of fixed costs, that is $\pi^T(\theta)$ and $\pi(\theta)$.

Proposition 3. *The decision to invest in ICT*

- (i) There is a productivity cutoff θ^{*T} defined by $\pi^T(\theta^{*T}) = \pi(\theta^{*T})$ so that firms invest in ICT if and only if $\theta \geq \theta^{*T}$;
- (ii) The cutoff θ^{*T} is increasing in the per unit cost of ICT, w_{ICT} ;
- (iii) The cutoff θ^{*T} is increasing in the adjustment cost Ψ .

Recall that unit variable costs are constant in output and that they decrease with ICT for all firms. Firms with larger θ are able to diffuse the fixed cost Ψ over a larger base of units of output that are produced at a lower variable cost, until reaching a critical point θ^{*T} (point i). The critical point is achieved for larger levels of firms productivity as the unit cost w_{ICT} or the adjustment cost become larger Ψ (points ii and iii).

For an intuition see Figure 8. The blue curve represents profits without ICT. The red curve represents profits with ICT. The dotted red line represents hypothetical profits with ICT if the adjustment costs of ICT were zero and lies above the blue line for all θ , implying that all firms would invest in ICT without adjustment costs. Increases in w_{ICT} reduce the slope of the red line, whereas increases in Ψ shift the curve downwards. The implication of this result is that more productive larger firms invest in ICT whereas less productive smaller firms are not able to cover the adjustment costs of investment and produce applying a less efficient combination of inputs. The result creates cross-sectional correlation between investment in ICT and size, task complexity, wages, and skill intensity, as per Proposition 2. It also highlights that investment in ICT depends on market conditions represented by the price of ICT and the costs of adjustment.

Proposition 3 refers to firm-level variables that are predictors of investment in ICT. We now turn to describing changes in firm behavior due to ICT.

Proposition 4. *Within firm changes due to ICT*

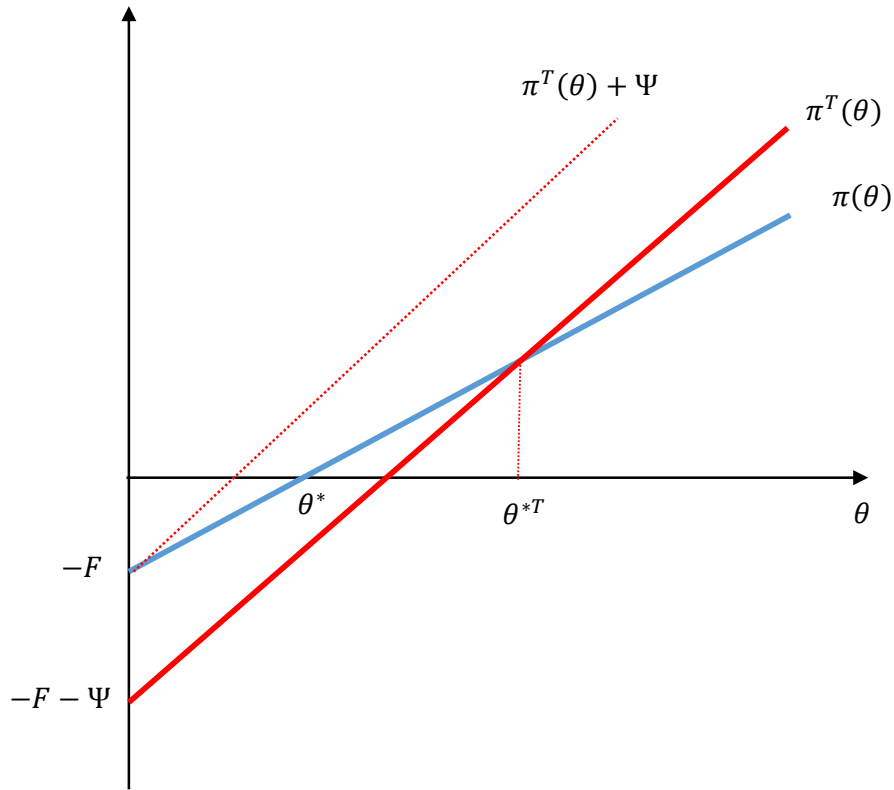
Assume that for a given θ , $\pi^T(\theta) > \pi(\theta)$, then

- (i) $x^T(\theta) > x(\theta)$;
- (ii) $w_L^T(\theta) > w_L(\theta)$ and $w_H^T(\theta) > w_H(\theta)$;
- (iii) $i^{*T}(\theta) < i^*(\theta)$.

Firms invest in ICT when profits are larger compared to a situation of no ICT. The increase in profits is derived from a reduction in costs. The lower variable unit cost implies a lower price and higher quantity of output (i). The increase in profits that results from the ICT investment is shared with workers through the fair-wage schedules, and thus wages go up for both skilled and unskilled workers (ii). We have that $s^T(\theta) < w_H(\theta)$ and that $w_L^T(\theta) > w_L(\theta)$; as a result, a smaller share of tasks is assigned to unskilled labor (iii) (Figure 9).

Regarding production of tasks, for the same reason as point (iii) above the participation of tasks carried out with the combination of skilled labor and ICT increases (Figure 10). These are the more complex tasks. Conditional on output, there is a substitution effect whereby the production of complex tasks increases and the production of non-complex tasks decreases. Total production of tasks depends on output. Production of complex tasks

Figure 8. The Decision to Invest in ICT



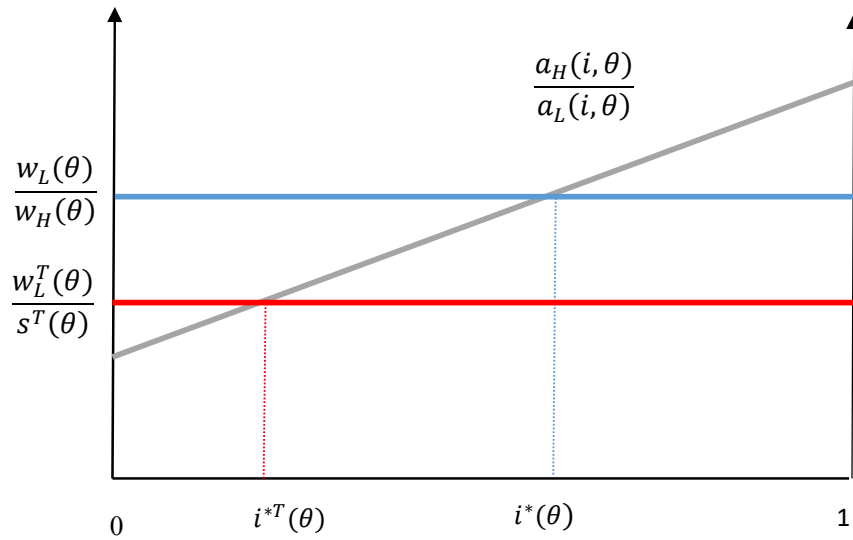
The solid blue curve represents profits with no ICT. Firms with productivity below θ^* do not break even and exit the market. The solid red curve represents profits with ICT. Firms with productivity below θ^{*T} are efficient enough to cover the adjustment cost of investment Ψ and choose to invest in ICT. Firms with productivity between θ^* and θ^{*T} stay in the market but do not invest in technology.

unambiguously increases, while production of non-complex task increases only if the increase in output is sufficiently high to compensate the negative substitution effect.⁸

This proposition provides predictions for within-firm variation due to ICT. Firms that invest in ICT experience a reduction in variable costs, become larger in terms of sales, pay higher wages to both skilled and unskilled workers, perform a larger share of tasks with a combination of skilled labor and ICT, and increase the relative production of complex tasks.

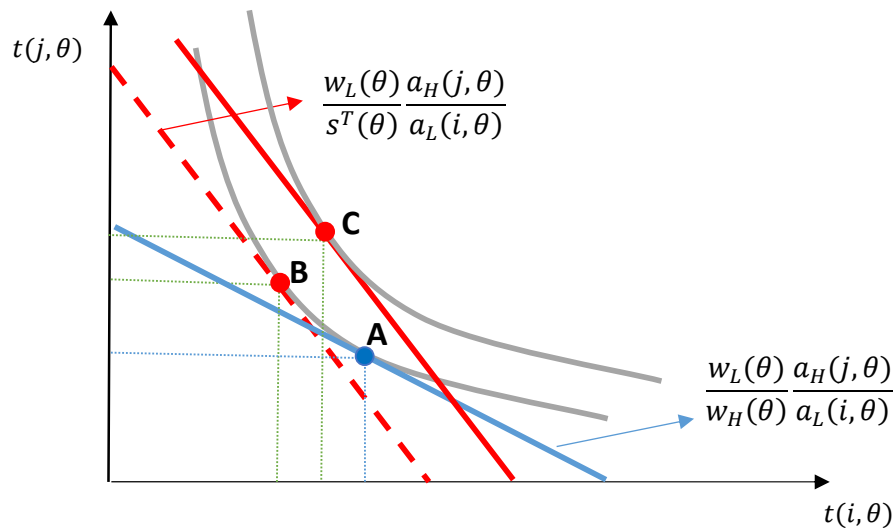
⁸ In Figure 10, point A represents a scenario in which ICT is not available. When ICT is available the firm chooses point C. The movement from A to B, which is a movement along an isoquant, is a substitution effect, whereas the movement from B to C, which is a movement along a ray through the origin (not shown), is an output effect. Production of complex tasks unambiguously increases, whereas the direction of change in production of non-complex tasks depends on the opposing forces of the substitution and output effect.

Figure 9. Assignment of Skilled and Unskilled Workers to Tasks. Investment in ICT



The graph compares the assignment of workers to tasks with ICT (in red) and without ICT (in blue). ICT increases the relative cost of unskilled workers and as a result a smaller set of tasks is carried out with unskilled labor.

Figure 10. Combination of tasks. Substitution and total effects. Investment in ICT



The graph compares the combination of more complex tasks (j , vertical axis) and less complex tasks (i , horizontal axis) with ICT (in red) and without ICT (in blue). ICT increases the participation of more complex tasks. The dashed red line represents the change in combination of tasks conditional on output (substitution effect, A to B), whereas the parallel solid red line shows the total change in the combination of tasks (A to C).

Employment of skilled and unskilled workers

We now discuss the effects of ICT on firm-level skill intensity and employment by worker type. As a first comment it is important to remark that the effect of ICT on the skill ratio is ambiguous. The ambiguity stems from the flexibility of the model, which accommodates situations in which skilled workers and technology are complements or substitutes; a feature that is captured by the elasticity of substitution σ .

For a firm that invests in ICT, the skill ratio is given by

$$\frac{H^T(\theta)}{L^T(\theta)} = \left(\frac{s^T(\theta)}{w_H^T(\theta)} \right)^\sigma \frac{w_L^T(\theta)}{w_H^T(\theta)} \frac{1 - i^{*T}(\theta)}{i^{*T}(\theta)}.$$

Investment in ICT affects the relative demand for skilled workers through three channels (or three different substitution effects): the fraction of tasks that are performed with skilled or unskilled workers, $i^{*T}(\theta)$; the quantity produced of each task; and the substitution between skilled labor and ICT capital. The first two channels work against unskilled workers and in favor of the CES skilled workers-ICT combination. The third channel is represented by the ratio $\left(\frac{s^T(\theta)}{w_H^T(\theta)} \right)^\sigma$, which is smaller than one, thus working against skilled workers and in favor of ICT. This effect is magnified as the elasticity of substitution between skilled labor and ICT capital increases.

The following proposition describes several extreme cases and the consequences on labor composition.

Proposition 5. *ICT and labor composition*

- (i) Assume $w_H(\theta) < w_{ICT}$, then $\lim_{\sigma \rightarrow \infty} H^T(\theta) = H(\theta)$ and $\lim_{\sigma \rightarrow \infty} L^T(\theta) = L(\theta)$.

If skilled labor and ICT are perfect substitutes and the complex tasks are more efficiently produced with skilled labor than with ICT, firms do not invest in ICT and there is no impact on employment and wages.

- (ii) Assume $w_H(\theta) > w_{ICT}$, then $\lim_{\sigma \rightarrow \infty} H^T(\theta) = 0$ and $\lim_{\sigma \rightarrow \infty} L^T(\theta) < L(\theta)$.

If skilled labor and ICT are perfect substitutes and the complex tasks are more efficiently produced with ICT than with skilled labor, firms invest in ICT and do not employ skilled workers. Employment of unskilled workers is reduced as ICT takes over some tasks that were produced by unskilled workers in the absence of ICT.

$$(iii) \quad \lim_{\sigma \rightarrow 1} L^T(\theta) = 0$$

A lower elasticity of substitution represents a situation in which skilled labor and ICT are better complements. The stronger the complementarity between skilled workers and ICT, the larger the savings in costs and the larger the share of tasks that are produced with the skilled labor-ICT combination. Given that $\lim_{\sigma \rightarrow 1} s^T(\theta) = 0$, there is no employment of unskilled workers in the limit.

Summing up Proposition 5. As complementarity between skilled labor and ICT increases (lower σ), the share of skilled labor in total firm employment becomes increasing in ICT. For a given σ , the share of skilled labor further depends (negatively) on the wage of skilled labor $w_H^T(\theta)$ relative to the price of technology $s^T(\theta)$; this effect is magnified by σ .

Regarding the absolute level of employment by worker type, the effects of ICT are ambiguous as well. We start by discussing unskilled employment. Conditional on a given level of output, unskilled workers are replaced by the CES combination of skilled workers and ICT. The substitution of unskilled workers takes place through two channels: a smaller set of tasks is assigned to unskilled labor (as argued in Proposition 4 and depicted in Figure 9); and the participation of unskilled tasks on output decreases (Figure 10). These effects work in the direction of reducing the demand for unskilled workers. At the same time, the output expansion due to the reduction in variable costs works in the direction of increasing the demand for unskilled workers. The overall effect of ICT adoption on employment of unskilled workers is positive if the output effect dominates the substitution effects.

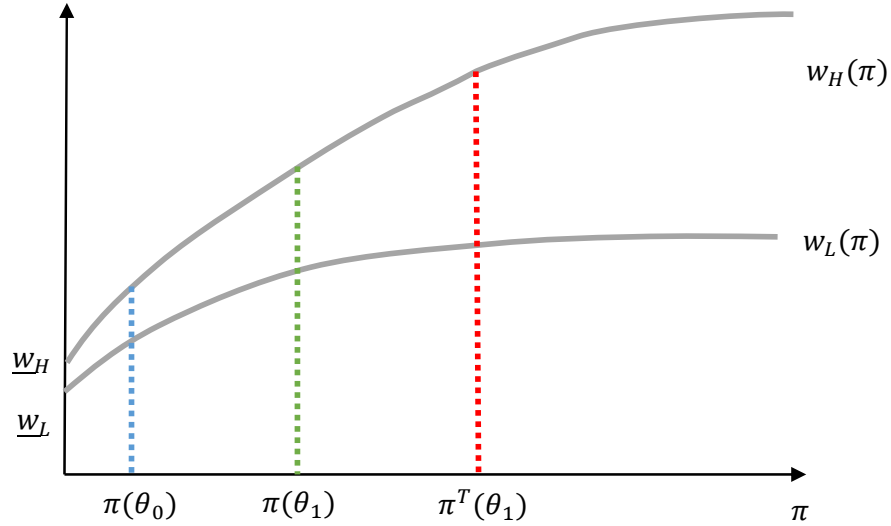
In the case of skilled employment both the output effect and the two substitution effects mentioned above increase the demand for skilled workers through an increase in the demand for the CES skilled workers-ICT combination. There is however the issue of whether skilled labor and ICT are substitutes or complements. If their elasticity of substitution σ is sufficiently small, employment of skilled workers increases with ICT. Notice that regardless of whether the absolute levels of skilled and unskilled employment increase or decrease, firm-level wages of both worker types increase due to rent-sharing. This implies that while some workers may be displaced by ICT, other workers in the same firm are better off after ICT due to the increase in wages.

Wage inequality

So far we have assumed that the skilled to unskilled ratio is constant in firm profits. This needs not be so. In this section we assume that the rent-sharing schedules are relatively

more increasing in profits for skilled workers (Figure 11). In other words, the wages of skilled workers are more tied to firm performance than the wages of unskilled workers. This is

Figure 11. The Increase in Fair-Wage Schedules is not proportional



The curves $w_H(\pi)$ and $w_L(\pi)$ are the rent-sharing wage schedules of skilled and unskilled workers. As profits increase, the relative wage $w_H(\pi)/w_L(\pi)$ increases as well. The wage gap is higher in more productive firms (green dotted line and blue dotted line), and is higher after ICT (red dotted line and green dotted line).

compatible with several situations. For example, larger firms provide more on-the-job training for skilled workers; since it is more costly for them to lose skilled workers to other firms, they pay higher wages to secure the workers' commitment. Another example is one in which there is more variance in the effort that skilled workers can exert, as on average the tasks that they perform are more complex, and therefore require a tighter incentive scheme. The less tight incentive scheme of unskilled workers may also result from higher risk aversion. These notions are supported in practice by the fact that often CEOs and managers receive bonuses and are compensated with company stocks, tied to firm performance.

Proposition 6. Wage inequality

Assume that skilled and unskilled wages increase at different rates so that $\frac{w_H(\pi)}{w_L(\pi)}$ is increasing in π . Then

- (i) $\frac{w_H(\theta)}{w_L(\theta)}$ is increasing in θ .
- (ii) $\frac{w_H^T(\theta)}{w_L^T(\theta)} > \frac{w_H(\theta)}{w_L(\theta)}, \forall \theta > \theta^{*T}$.

This scenario represents a situation in which the skill premium is larger in more productive larger firms, and in which the skill premium increases with investment in ICT. Point (ii) is derived from the fact that profits increase due to investment in ICT. Figure 11 represents this scenario. The blue and green dotted lines represent the difference in skill premium between a small and large firm, while the green and red lines show the skill premium for the same large firm after investment in ICT.

Notice that as firms become more productive, the increase in the relative efficiency in the use of skilled labor (ratio of inverse unit requirements) makes skilled workers more cost effective and firms more skill intensive. The increase in the relative wage of skilled workers works in the opposite direction and partially offsets the increase in their relative efficiency. Empirically it is usually found that larger, more productive firms are on average more skill intensive, which suggests that as firms become more productive the relative efficiency in the use of skilled labor increases at a larger rate than the relative wage of skilled workers.

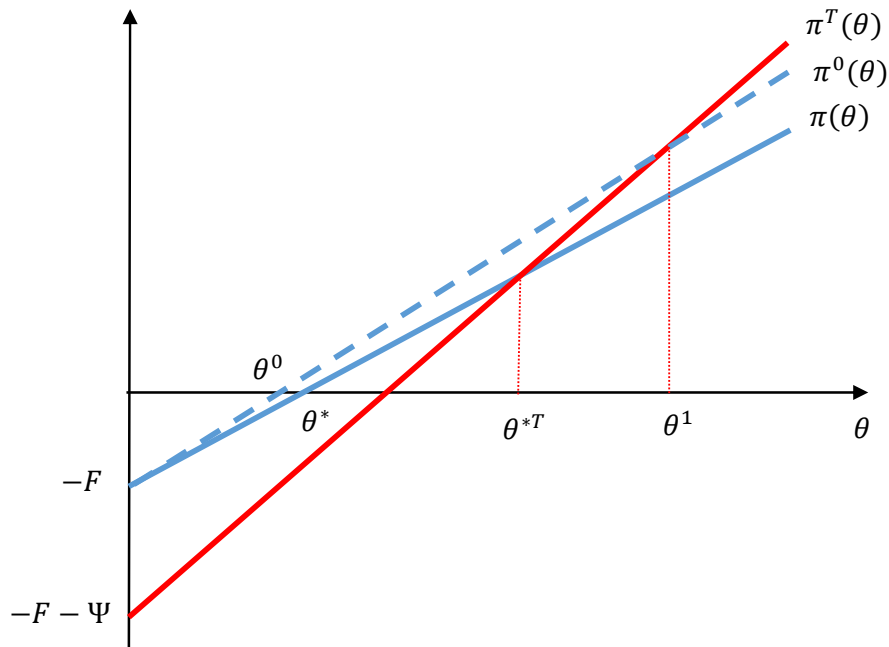
Industry-level outcomes after adoption of ICT

Differences in productivity across firms lead to different firm-level outcomes that we have discussed in the previous sections. In our previous description, we have considered the decisions faced by small firms and the within-firm changes after investing in ICT. We now turn to comparing industry-level equilibria without and with investment in ICT.

Investment in ICT presents to firms as an opportunity to reduce variable costs, reduce prices, increase output, and is thus in principle profit enhancing. For some firms, however, the news is not so good. Low-productivity firms are not able to afford the fixed costs of ICT and choose not to adopt new technology. High-productivity firms, on the other hand, do adopt ICT and increase output. The increase in competition reduces the residual demand for low productivity firms, and their output and profits fall. The firms with lowest productivity are pushed out of the market.

This mechanism is depicted in Figure 12. There is an initial situation in which investment in ICT is not available. Profits under the initial situation are plotted with a dashed blue curve and denoted by $\pi^0(\theta)$. The cutoff productivity in the initial situation is θ^0 . Firms with productivity below θ^0 exit the market. We now turn to a second situation in which firms have the option to invest in ICT. The solid red and blue curves represent profits for firms that choose to invest and not to invest in ICT, respectively denoted by $\pi^T(\theta)$ and $\pi(\theta)$. The parameters θ^{*T} and θ^* are the cutoffs for investing in ICT and exiting the market. Consider the difference between $\pi(\theta)$ and $\pi^0(\theta)$. The curve $\pi^0(\theta)$ lies above the curve $\pi(\theta)$ because under $\pi(\theta)$ firms that do not invest in ICT face a more intense competition from firms that do

Figure 12. Industry equilibrium with and without ICT



The dashed blue curve represents profits in an initial situation “0” in which firms do not have the option to invest in ICT. The parameter θ^0 is the productivity cutoff, so that firms with productivity below θ^0 exit the market because they do not break even. The solid blue and red curves represent profits in a situation in which ICT is available. As before, the solid blue curve represents profits for a firm θ^{*T} that does not invest in ICT, given the equilibrium response of all other firms, and the red curve represents a similar profit curve for a firm that does invest in ICT.

invest in ICT. The cutoff θ^* is therefore larger than the cutoff θ^0 , that is, more firms choose to exit the market in a situation in which ICT is available.

Firms that remain in the market can be classified in three groups. First, low productivity firms, with productivity parameter between θ^* and θ^{*T} , which do not invest in ICT and for which output and profits are lower than under the initial situation with no ICT. Second, medium-productivity firms, with productivity parameter between θ^{*T} and θ^1 (see Figure 12), which do invest in ICT, but for which the reduction in variable costs is not high enough and their output and profits are lower than under the initial situation. Finally, high-productivity firms, with productivity parameter above θ^1 , which choose to invest in ICT and for which output and profits are higher than under the initial situation. Summing up, the availability of ICT concentrates production around high productivity firms. The lowest productivity firms exit the market; low and medium-productivity firms become smaller; whereas high-productivity firms become larger. Further, the availability of ICT may induce entry of new firms.

By aggregating over the distribution of firm productivity parameters G we can define aggregate demand for skilled and unskilled labor, denoted by $\bar{H}(\theta)$ and $\bar{L}(\theta)$, and given by

$$\bar{H}(\theta) = \int_{\theta^*}^{\theta^{*T}} H(\theta) dG(\theta) + \int_{\theta^{*T}}^{\theta^1} H^T(\theta) dG(\theta) + \int_{\theta^1}^{\infty} H^T(\theta) dG(\theta),$$

$$\bar{L}(\theta) = \int_{\theta^*}^{\theta^{*T}} L(\theta) dG(\theta) + \int_{\theta^{*T}}^{\theta^1} L^T(\theta) dG(\theta) + \int_{\theta^1}^{\infty} L^T(\theta) dG(\theta),$$

We split aggregate demand in three terms, corresponding to low, medium and high productivity firms. In the previous sections we discussed conditions under which labor demand increases at the firm level. Let us first consider unskilled workers. Investment in ICT generates negative substitution effects and ambiguous output effects. These effects are different across the three groups of firms. In the case of low productivity firms, there are no substitution effects (they choose not to invest in ICT) and the output effect is negative. In the case of medium productivity firms, because they invest in ICT the substitution effect is negative, while the output effect is negative as well. Therefore, for these two groups of firms the total effect on unskilled labor demand is negative.⁹ For high productivity firms, the substitution effect is negative and the output effect is positive. The higher the productivity, the more likely that the output effect dominates the substitution effect and that demand for unskilled labor increases with ICT due to an increase in firm size. The aggregate effect of ICT on $\bar{L}(\theta)$ depends on the distribution of firms G . The more concentrated production becomes around the most productive firms, the more likely that the effect of ICT on unskilled labor demand is positive.

Consider now the case of skilled workers. We focus on the case in which ICT and skilled workers are complements, that is, situations in which the elasticity of substitution in production is sufficiently small. In this situation the substitution effect is positive and works in the direction of increasing demand for skilled labor, while the output effect is positive as well. In the case of low productivity firms, there is no substitution effect (due to lack of investment in ICT) and the output effect is negative, therefore there is a decrease in skilled labor demand. In the case of medium-productivity firms, the substitution effect is positive and the output effect is negative, therefore the effect on skilled labor demand is ambiguous. Finally, in the case of high productivity firms both the substitution and output effects are positive, and demand for skilled labor unambiguously increases. The aggregate effect of ICT on $\bar{H}(\theta)$ again depends on the distribution of firms G and other model parameters.¹⁰

As a final caveat, the two equilibria that we discuss are situations of partial equilibrium as the wage schedules are taken as given. Changes in aggregate labor demand,

⁹ There could be positive second-order effects operating through changes in wages through the rent-sharing schedules, compared to the situation with no ICT.

¹⁰ As before, there could be second-order wage effects working through the rent-sharing mechanism.

skilled and unskilled, affect wage schedules in cases of large industries or industries with specific factors or mobility costs. These effects have been studied theoretically and empirically, without considering wage heterogeneity, by a large share of the tasks-approach literature of labor markets and technology adoption. In this paper we abstract from general equilibrium wage effects while instead focusing on firm-level outcomes and allowing for imperfect competition in labor markets.

4. Conclusions

We develop a theoretical framework that expands the task-based models of technical progress and labor markets to allow for firm heterogeneity and wages that vary across firms. Our model is compatible with the empirical observation that more productive firms are larger, are more skill intensive, and pay higher wages across skill categories. Regarding investment in ICT, our model predicts that the decision to invest in ICT depends on firm size and labor market characteristics. As a result of investment in ICT, firms grow, become more intensive in complex tasks, and become more skilled intensive as long as skilled labor is complementary to ICT. Even if firms become more skilled intensive, the overall effect of ICT adoption on employment of unskilled workers could be positive if the increase in output due to the reduction in variable costs is sufficiently high. At the aggregate level, changes in employment depend on the distribution of firm productivity and the resulting concentration of production, as output effects become largest for the highest productivity firms. The changes in skill intensity and the absolute level of employment by worker type are questions open for empirical research. Workers who remain employed are better off because their wage increases with ICT. To the extent that skilled workers have more bargaining power than unskilled workers, or that their wage scheme is more tied to firm performance, wage inequality at the firm-level increases with ICT.

References

- Acemoglu D. and D. Autor (2011): "Skills, Tasks and Technologies: Implications for Employment and Earnings". *Handbook of Labor Economics*, vol. 4b, pp. 1044—1166.
- Acharya, V., R. Baghai, and K. Subramanian (2013): "Labor Laws and Innovation," *Journal of Law and Economics*, vol. (56), pp. 997—1037.
- Akerman, A., I. Gaarder, and M. Mogstad (2015): "The Skill Complementarity of Broadband Internet," *The Quarterly Journal of Economics*, vol.130(4), pp. 1781—1824.
- Amiti, M. and D. Davis (2011): "Trade, Firms, and Wages: Theory and Evidence," *Review of Economic Studies*, vol. 79, pp. 1—36.
- Autor D. H., and D. Dorn (2013): "The growth of low-skill service jobs and the polarization of the US labor market," *The American Economic Review* vol. 103(5), pp. 1553—1597.

- Autor, D.H., L.F. Katz and M.S. Kearney (2008): "Trends in U.S. Wage Inequality: Revising the Revisionists," *The Review of Economic and Statistics*, vol. 90(2), pp. 300—323.
- Autor, D. H., L. F. Katz, and A. B. Krueger (1998): "Computing Inequality: Have Computers Changed the Labor Market?," *Quarterly Journal of Economics*, vol. 113(4), pp. 1169—1213.
- Autor, D. H., F. Levy, and R. J. Murnane (2003): "The Skill Content of Recent Technological Change: An Empirical Exploration," *The Quarterly Journal of Economics*, vol. 118(4), pp. 1279—1333.
- Aw, B.Y., M. J. Roberts, and D.Y. Xu (2011): "R&D Investment, Exporting, and Productivity Dynamics," *The American Economic Review*, vol. 101(4), pp. 1312—1344, June.
- Bartelsman, E., P. Gautier and J. de Wind (2016): "Employment Protection, Technology Choice, and Worker Allocation," *International Economic Review*, vol. 57(3), pp. 787—826, August.
- Bartelsman, E.J. and J. Hinloopen (2005): "Unleashing Animal Spirits: Investment in ICT and Economic Growth", in L. Soete and B. ter Weel (eds.), *The Economics of the Digital Society*, Edward Elgar, pp. 272 – 304.
- Berman, E., J. Bound, Z. Griliches (1994): "Changes in the Demand for Skilled Labor within U.S. Manufacturing: Evidence from the Annual Survey of Manufactures," *The Quarterly Journal of Economics*, vol. 109(2), pp. 367—397.
- Berman, E., J. Bound, S. Machin (1998): "Implications of Skill-Biased Technological Change: International Evidence," *The Quarterly Journal of Economics*, vol. 113(4), pp. 1245—1279, November.
- Bernard, A. and B. Jensen (1999): "Exceptional Exporter Performance: Cause, Effect, or Both?," *Journal of International Economics*, vol. 47, pp. 1—25.
- Bloom, N., R. Sadun, and J. Van Reenen (2012): "Americans Do I.T. Better: US Multinationals and the Productivity Miracle," *American Economic Review*, vol. 102(1), pp. 167—201.
- Bound, J. and G. Johnson, "Changes in the Structure of Wages in the 1980's: An Evaluation of Alternative Explanations," *The American Economic Review*, vol. 82(3), pp.371—392.
- Bloom, N., M. Draca, and J. Van Reenen. (2016): "Trade induced technical change? The impact of Chinese imports on innovation, IT and productivity." *The Review of Economic Studies*, vol. 83(1), pp. 87—117.
- Bresnahan, T., Brynjolfsson, E. and M.L. Hitt (2002) "Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-Level Evidence," *The Quarterly Journal of Economics*, MIT Press, vol. 117(1), pp. 339—376, February.
- Brynjolfsson, E., and L.M. Hitt (2003): "Computing productivity: Firm-level evidence," *Review of Economics and Statistics*, vol. 85(4), pp. 793—808.
- Card, D. and T. Lemieux (2001): "Dropout and Enrollment Trends in the Postwar Period: What Went Wrong in the 1970s?," in J. Gruber ed., *Risky Behavior among Youths: An Economic Analysis*, University of Chicago Press for the NBER.
- Card, D. and T. Lemieux (2001b): "Can Falling Supply Explain the Rising Return to College for Younger Men? A Cohort-Based Analysis," *The Quarterly Journal of Economics*, vol. 116(2), pp. 705—746.

- Di Nardo, J., and J.P. Pischke (1997): "The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?," *Quarterly Journal of Economics*, vol. 112(1), pp. 291—303.
- Draca, M., R. Sadun, and J. Van Reenen (2007): "Productivity and ICT: A Review of the Evidence", in Avgerou, Mansell, Quah, and Siverstone, eds., *Handbook of Information and Communication Technologies*, 100-147, Oxford, UK. Oxford University Press.
- Koeniger, W. (2005): "Dismissal costs and innovation," *Economics Letters*, vol. 88(1), pp. 79—84, July.
- Goldin, C., and L. Katz (1998): "The Origins of Skill Capital Complementarity," *Quarterly Journal of Economics*, vol. 113(3), pp. 693—732.
- Goos, M. and A. Manning (2007): "Lousy and Lovely Jobs: The Rising Polarization of Work in Britain," *Review of Economics and Statistics*, vol. 89, pp. 118—133.
- Goos, M., A. Manning, A. Solomons (2014): "Explaining Job Polarization: Routine-Biased Technological Change and Offshoring," *The American Economic Review*, vol. 104(8), pp. 2509—2526, August.
- Gust, C., and J. Marquez (2004): "International Comparisons of Productivity Growth: The Role of Information Technology and Regulatory Practices", *Labour Economics*, vol. 11(1), pp. 33—58, February.
- Jorgenson, D.W., M.H. Ho, and K.J. Stiroh (2008): "A Retrospective Look at the U.S. Productivity Growth Resurgence," *Journal of Economic Perspectives*, vol. 22(1), pp. 3—24.
- Katz, L. F., and K. M. Murphy (1992): "Changes in Relative Wages, 1963-1987: Supply and Demand Factors," *The Quarterly Journal of Economics*, vol. 107(1), pp. 35—78.
- Krueger, A. B. (1993): "How Computers Have Changed the Wage Structure: Evidence from Microdata," *The Quarterly Journal of Economics*, vol. 108(1), pp. 33—60.
- Krusell, P., L. Ohanian, J. V. Ríos-Rull, G. L. Violante (2000): "Capital-Skill Complementarity and Inequality: A Macroeconomic Analysis," *Econometrica*, vol. 68(5), pp. 1029—1053.
- Kugler, M. and E. Verhoogen (2012): "Prices, Plant Size, and Product Quality," *Review of Economic Studies*, vol. 79(1), pp. 307—339, January.
- Machin, S. and J. Van Reenen (1998): "Technology and Changes in Skill Structure: Evidence from Seven OECD Countries," *The Quarterly Journal of Economics*, vol. 113(4), pp. 1215—1244.
- Melitz, M. (2003): "The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity," *Econometrica*, vol 71., pp. 1695—1725.
- Michaels, G., A. Natraj, and J. Van Reenen (2014): "Has ICT Polarized Skill Demand? Evidence from Eleven Countries over Twenty-five Years," *Review of Economics and Statistics*, vol. 96(1), pp. 60—77.
- Oliner, S.D., D.E. Sichel, and K.J. Stiroh (2007): "Explaining a Productive Decade," *Brookings Papers on Economic Activity*, (1), pp. 81—137.
- Saint-Paul, G. (2002), "Employment Protection, International Specialization, and Innovation," *European Economic Review*, vol. 46(2), pp. 375—395.

Samaniego, R. (2006): "Employment Protection and High-Tech Aversion," *Review of Economic Dynamics*, vol. 9(2), pp. 224—241.

Syverson, C. (2011): "What Determines Productivity," *Journal of Economic Literature*, vol. 49(2), pp. 326—365.

van Ark, B., M. O'Mahoney and M. Timer (2008): "The Productivity Gap between Europe and the United States: Trends and Causes." *Journal of Economic Perspectives*, vol. 22(1), pp. 25—44.

Verhoogen, E. (2008): "Trade, Quality Upgrading, and Wage Inequality in the Mexican Manufacturing Sector," *The Quarterly Journal of Economics*, vol. 123(2), pp. 489—530.