The role of general and firm-specific training for new technology adoption and economic growth: a critical review

Roberto Antonietti

Doctorate of research in *Law and Economics*
Department of Economics, University of Bologna
Strada Maggiore, 45
40125 Bologna
antonietti@spbo.unibo.it

Abstract♠

Aim of this article is to present an overview of the main economic literature focusing on the issue of how technology adoption and the accumulation of technical skills by firms affects the aggregate performance of economic systems. Since the analysis is labour-demand oriented, a differentiation between a 'mainstream' and a 'non-mainstream' approach is supposed to be crucial, the first being consistent with the neoclassical paradigm of the firm and human capital, while the second with the Schumpeterian paradigm and the so called view of the firm as a 'learning organization'.

Going through the basic models, the paper argues that while the mainstream approach is primarily based on production costs analyses and the capacity of the market and hierarchies to provide the specific skills in order for workers to deal with new technologies, non-mainstream approaches are mainly oriented to the analysis of dynamic competition, entrepreneurial/managerial skills and within-firm organizational learning processes that are necessary in order to cope with a changing environment.

Keywords: *specific training, learning, technology adoption, resource-based perspective, genetic algorithms*

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1. Introduction

The understanding of how new technologies impact firms and workers' skills has increasingly become important in the last twenty years, particularly after the recognition of the skill-biased nature of technological change. However, measures of skills at the firm level have been very limited, detailed firm-level measures of technology are difficult to obtain and longitudinal data on firms are not widely available.

It is commonly argued in the empirical literature as well that the diffusion of new technologies, and in particular new information technologies, has restructured workplaces and led to changes in the relative demand of skilled workers and new competencies (Autor *et al.*, 1998; Arnal *et al.,* 2001; Bresnahan *et al.*, 2002; Bartel *et al.*, 2003).

The way skills contribute to productivity improvements within firms is still something as a "black box". If there is general agreement that broadly defined human capital is important for economic growth, less is known about the mechanisms by which skills and knowledge contribute to a firm's pursuit of efficiency in production and the process of innovation and successful technology adoption.

This paper presents an overview of the main theoretical literature about within-firm technology adoption and, in particular, about the importance of workplace training as the most suited channel for creating and accumulating specific skills. The main research question concerns to what extent the successful (exogenous) adoption of new technologies by firms affects the aggregate performance of economic systems. In so doing, human capital accumulation through workplace training is crucial. Therefore, in order to answer this question and understand these macro-economic relations, an analysis of the micro-economic foundations seems to be useful and functional to the scope of this review, so that a further research arises here: what is the microeconomic impact of the adoption of new technologies on the firm's investment in specific human capital, namely on-the-job training?

In order to clearly fit all the relevant perspectives, it seems worth to identify first which categories of skills the adoption of new technology requires and, in a second stage, through which channels such skills are acquired by economic agents, namely workers and managers and/or entrepreneurs. The paper shows that '*mainstream*' approaches play the role of the master when dealing with workers' technical skills, whereas '*non-mainstream*' approaches seem to be particularly effective in dealing with entrepreneurial and/or managerial skills, and learning or cognitive aspects of the firm.

The paper is organized as follows. Sections 2 defines the context of analysis, and specifies the concept of 'adoption'. Section 3 presents the mainstream models of technology adoption and training, both at micro and at macro-economic level. Section 4 introduces the main theoretical cornerstones of the 'heterodox' approaches, putting particular emphasis on the different conception of the firm and the market they embrace and on the different idea of knowledge they develop. Finally, section 5 contains some concluding remarks.

2. Technology adoption and skills accumulation within the firm

Within the present context, '*adoption*' refers to the stage in which a technology is selected for use by an individual or an organization, namely the firm. More precisely, I am not interested here in studying the process of technology 'adoption' *per se*, nor the mechanisms through which a new technology spreads and arrives at the firm's gates. For this reason, in the paper neither the models of technology 'diffusion' nor the models of technology 'selection' will be discussed. The starting point of the analysis, instead, will be the moment in which the firm, after having exogenously selected the technology to adopt, faces the issue of its application within the production process, an issue that, in turn, appears to be intimately related to that concerning the firm's human capital investments. In this context, indeed, the term 'adoption' is much closer to the concept of 'implementation' rather than 'diffusion'.

The role of skills and knowledge within the firm can be considered part of the process of adoption and, in general, of the wider linkage between human capital and economic growth. In the presence of rapid technological change, firms face higher opportunities to adopt profitable technologies, thus improving the level of productivity.

Before proceeding with the analysis, two further issues need to be investigated: first, what broad categories of skills are required after the adoption of new technology; second, how such skills are acquired and accumulated over time.

What the evidence suggests is that:

(i) the adoption of new technologies increases the relative demand of skilled labour, by making skilled workers more productive and replacing the routine tasks usually performed by less-skilled individuals (*technology-skill complementarity* hypothesis). Using Bartel and Lichtenberg (1987) words, educated workforce has a comparative advantage in adopting new technologies. At the aggregate level, the increased supply of skilled labour allows firms to take up skill-complementary technologies and foster further inventions;

(ii) plants with higher levels of firm productivity also have higher workplace skills. However, technology adoption itself may not be the main driver of firm skill and productivity levels: in fact, firms appear to have a more skilled workforce already in order to be able to adopt more advanced technologies. The evidence, in this case, suggests that workers are better paid because they are abler to adapt to changing scenarios, rather than because they are utilizing new technologies (Aghion and Howitt, 2002);

(iii) the full productivity gains obtained from technical change, or through technology implementation, especially in the case of ICT, appear to require substantial changes in the workplace organization as well (Ichniowski, 1990; Ichniowski *et al.*, 1997; Arnal *at al.*, 2001). These changes can include flatter management structures, more intensive team work activities, and performance-related payment systems. Therefore, organizational change complements technical change, and the skills related to entrepreneurship and management gain importance.

What the evidence shows is, indeed, that two broad categories of skills appear to be important in affecting the search by firms of productivity improvements: *entrepreneurial/managerial* and employees' *technical* skills. In order to clarify this distinction, it is useful to think at the firm as an entity, or an organization, primarily characterized by problem-solving processes, so that it is possible to associate the two broad typologies of skills just mentioned to specific problem-solving abilities.

Entrepreneurial/managerial skills refer the capability, borne by the entreopreneur, or by the management of the firm where these two figures are separated, to provide the organizational skills required to oversee the effectiveness of production processes after the adoption of a new technology. *Managerial capability* is crucial in order to solve problems related to the opportunistic behaviour of the employees, to remove inefficiencies, to optimize the firm's performance and, in general, to deal with control and supervision issues. Important as well is the design of organizational structures that utilize technology and skill inputs effectively, and human resource management that ensures worker motivation and effort. The set of skills required to an entrepreneur or a manager is ample: from the strategic ability to adapt to a changing environment to the organizational and supervision skills to an awareness of information management processes. Human resource management practices, in particular, have been recently emphasised by the economic literature as the main tool for providing a coherent system of incentives that enhances the contribution of workers to firm productivity (Ichniowski, 1990).

Technical skills, on the other hand, refer to the ability and knowledge that employees have in order to effectively support the production process, to solve technical problems and to physically implement innovations within the production process. The workers' technical skills are only partly provided by the formal education system. Other behavioural features and cognitive capacities are important as well, and other channels are often involved in the production of such kind of knowledge: learning activities, experience, imitation. Thus, the link with the schooling system can become weaker when a significant subset of skills required are formed inside the firm or where the cognitive abilities sought are largely innate.

Who possesses such skills is a matter that varies according to the economic theory of the firm we consider. For instance, in the neoclassical paradigm, mainly represented by the so called *A-firm*, the ownership and the role of control, supervision, and management usually correspond to a unique character, the entrepreneur. In this case, it is possible to assign the managerial skills described above to the entrepreneur and the technical skills to the workforce. The theories of the firm developed by strategic management, on the other hand, clearly distinguish between the figure of the owner, or the stockholder, and the figure of the manager. In this case, is the latter who accumulates the managerial skills.

Again, if we consider the Ohnist-Tyotist paradigm of the firm, or the theories studying the processes of team-oriented production, we have that the figures of the manager and of the worker match each other, so that employees are ask to accumulate managerial skills as well.

Finally, in the literature focused on asymmetric information and the agency problem, managerial skills can be viewd as a prerogative of the *principal*, whereas technical skills of the *agent.*

What is important to stress is that technological shocks that somehow alter the production process require all kinds of workers to adapt, employers, managers, as well as employees.

3. Mainstream approaches

3.1. Production costs analysis: the human capital model

Mainstream theoretical models are usually based on the idea that technology adoption must be accompanied by firm-specific training, the reliability of its effect on the individual labour productivity being certain and positive. When the firm faces a rapid technological change, thus, the cost of adopting a new technology in terms of labour training can be significant. Neoclassic approaches implicitly embrace a static perspective of the firm, mainly adherent to the concept of production function and a 'Walrasian' idea of skills as determinants of both employers' and workers' earnings: skills are part of the broader concept of 'human capital' that, in turn, constitutes either a direct factor in the production function or an indirect factor if it primarily affects the input of labour. Therefore, changes in the intensity of training investments implies a change in the costs of production. According to this production costs perspective, the firm, in the most standard version, exists as a given "production set", it can be considered as an "island of technological knowledge" with a fixed edging shore and it is always able to draw on its technical set those production output and techniques that represent its rational response to a well defined business objective, usually identified in the profit maximization (Nelson and Winter, 1982, chapter 3). According to Bowles *et al.* (2001), skills are 'Walrasian' in that they are part of the broader concept of human capital that, in turn, is viewed as a factor in the production process in the neoclassical sense; the attributes required by the parties in moving to equilibrium are not considered and the law of diminishing returns dominates.

In such a framework, employee training due to technology adoption can be considered as a special case of firm-provided worker training in general for whatever reason. The basis for the modern economic analysis of training is 'human capital theory', which has represented the benchmark for all the subsequent empirical and theoretical analyses, both at micro and at macroeconomic level. Without attempting to give a comprehensive guide of the historical development of this theory, it is worth reviewing its core models, in particular those concerning the labour demand side, namely the training investment decisions made by firms.

The initial ideas on the nature and the role of specific training are developed by the "School of Chicago" in the early 1950s, notably by economist like Jacob Mincer (1962), Gary Becker (1964) and Theodore W. Schultz (1961, 1963). The first who starts generating a formal set-up of within-firm training is Gary Becker in his 1964 book, while Mincer, in his 1962 article, provides the first definitional and empirical analysis of on-the-job training costs. One of the major development in the theory of training comes with the distinction between training that is relevant to a wide variety of tasks and across firms and training that is more specific to the job and the firm, the latter being the main subject of this review.

- **General training** increases the marginal labour productivity of trainees by the same amount in the firm providing the training as well as in other firms.
- **Specific training**, instead, increases the marginal productivity only within the training-provider firm.

In particular, the resources usually spent by firms in familiarizing new employees with their organization are a form of specific training because productivity is raised more in the firms acquiring this knowledge than in other firms. The same idea can be applied when familiarizing with new technologies or innovations within the firm. Different are also the incentives for the firm to pay the costs of such kinds of training. In fact, firms are more willing to provide general training only if they do not have to bear any of the relative costs, since they will not be able to reap all the benefits. Individuals who get general training are more willing to pay the costs since training will raise their future wages. Reversely, in the case of specific training, workers would not recoup their investments in specific skills and would be willing to share some of the costs of specific training investments.

Following Becker, the basic human capital model can be presented using a two-period market scenario. In the first period individuals decide whether or not to train; there are two kind of jobs, *skilled* and *unskilled,* the former requiring a certain amount of training in order to be efficiently performed. The essence, thus, is that the labour market entrants choose between training and job search in the first period. As far as this model is concerned, full employment is assumed in all labour markets and all trained workers take up skilled employment.

Suppose w_U to be the unskilled wage rate, w_H the skilled wage rate, $\rho = 1/(1+r)$ the discount factor which varies across individuals, *r* the individual discount rate, w_0 the wage rate of the trainee in the first period. Further, assume that $w_0 < w_U < w_H$.

If no training takes place at all, we have the usual equilibrium condition between the wage rate and the marginal product:

$$w_U = MPL. \tag{1}$$

If, on the contrary, training occurs in the first period, then we have the following equilibrium condition - reflecting Adam Smith's idea of '*compensating differentials*' - that the firm will provide training whenever the discounted returns are at least as large as the relative costs:

$$\underbrace{w_0 + \tau + \rho \cdot w_H}_{costs} = \underbrace{MPL_0 + \rho \cdot MPL_1}_{benefits} \tag{2}$$

where τ represents the actual training costs. Equation (2) states that total benefits from training, in terms of labour productivity, must be equal to total costs, in terms of wage and direct outlays. In order to see how costs and benefits are distributed among the agents, let's define total returns to the firm of training as

$$TB = \rho \cdot (MPL_1 - w_H) \tag{3}$$

and total costs as

$$TC = mpl - MPL_0 + \tau \tag{4}$$

where *mpl* represents the marginal product that could have been produced without any training (i.e. the opportunity cost of training). Substituting equations (3) and (4) into (2) we obtain:

$$TB + mpl = w_0 + TC\,. \tag{5}$$

If *TB = 0*, we are in the case of general training, since the firm is not able to reap any benefit from training. Since trainees can command their marginal productivity in other firms, the wage rate for such workers will always be set at the marginal product. From (5) and (4) respectively we get

$$w_0 = mpl - TC = MPL_0 - \tau\,. \tag{6}$$

The above expression shows the qualitative results reached before about general training finance. In fact it is easy to see that in the case of general training current wages are set below the current opportunity cost of training (*mpl*); indeed, workers rather than firms bear the relative costs and reap the relative benefits.

In the case of *specific training*, assume that workers can no longer transfer across firms the skills they have acquired on the job so that they are useful only in the training-provider firm. In equilibrium, the firm will attempt to acquire all the gains from training and set them equal to costs. Therefore we have:

$$mpl = w_0 \text{ and } TB = TC. \tag{7}$$

Workers would be indifferent between training and unskilled work. If they would be able to appropriate the gains from training, then:

$$mpl - TC = w_0 \text{ and } TB = 0. \tag{8}$$

However, as Becker argues, the willingness of workers or firms to invest in specific training depends on the likelihood of labour turnover. On the one side, in fact, firms would not waste resources for training if the workers can quit to another job, while, on the other, workers would not collect any return if the firm fires them after the training costs have been borne. Labour turnover, then, becomes important when some costs are charged over employees or firms, which are the effects of specific training.

In general, if α is the fraction of the gain from training accruing to the firm and, therefore, the relation $TB = (1-\alpha)\cdot TC$ holds, equation (9) below gives the training wage equation for specific training:

$$w_0 = mpl - (1-\alpha)\cdot TC\,. \qquad (9)$$

Becker does not provide any rigorous explanation as to how α is determined, but just argues that it depends on the relations between quit rates and wages, layoff rates and profits, and other factors such as cost of funds, attitudes toward risk and desire for liquidity.

At this stage of the analysis, it is worthy to add some interesting empirical evidence supporting human capital idea. This evidence is mainly provided by Jacob Mincer, who first attempts to investigate the interplays between technological change and on-the-job training. In his 1962 article, Mincer defines on-the-job training costs as "the expense brought about by sub-standard production of new employees while learning their job assignments and becoming adjusted to their work environment, the dollar value of time spent by supervisors an other employees who assist in breaking in new employees on their job assignments and, finally, costs of organized training programs".

Starting from the idea that technological change is usually biased towards human capital rather than towards unskilled labour, and using multi- or total-factor productivity growth indices as a measure of technical change, Mincer (1989) finds that:

(i) a more rapid pace of technological progress increases the utilization of human capital inputs, formed at school and on the job, by making their acquisition more profitable, a result in line with other empirical contributions, as in Bartel and Lichtenberg (1987), Gill (1988) and Lillard and Tan (1986);
(ii) when technical innovations are in some degree firm-specific, on-the-job investments in worker training lead to more durable attachments to firms and less job mobility. As a result, regardless of the degree of firm-specificity, increased on-the-job training investments steepen employees wage profiles;
(iii) the time sequence in human capital adjustments to new technologies can differ as between the hiring of workers with needed education and the training or retraining of others. Skills adjustments can be first obtained by hiring policies, and then by training as the process becomes more routinized;
(iv) training processes follow technological change with a lag, while the utilization of educated workers is a concurrent response;

(v) if, on the one side, faster technological change requires more workers to be trained and more frequently, on the other its time length needs not to be longer.

Rounding up, training activities are more frequent when productivity growth is faster and in faster-growing industries.

3.1.1. Criticisms and further extensions of human capital theory

There are several gaps and inadequacies in the methodology adopted by human capital theorists.

The first critique is radical since it concerns the nature of the production process and of skills. Bowles and Gintis (1975) and Bowles *et al.* (2001) consider production as a social and not a purely technical process; the firm is a social construct and production is a process that, in turn, depends on the social relations to production. Following the fundamental tenets of the Marxist theory, production is a joint process in which raw materials are transformed into products but workers are also altered in terms of skills and consciousness. In addition, labour cannot be considered as a mere commodity or just as another input, and investments in humans cannot be associated to investments in physical capital. Human capital is multi-dimensional, including not only skills acquired at school but also other behavioural aspects and traits. Features like aptitude, motivation and communication are often considered by employers as more important than technical skills.

A second observation concerns the reason why employers and employees have to share training costs. In the model of Becker it is the uncertainty about post-training investments that drives the parties to set sharing contracts. Rather than uncertainty, positive and significant transaction costs may arise as the main motivation. In fact, when skills and training are specific to the firm, the costs of separation may be high: for firms, by one side, can be difficult and expensive to replace workers who quit the current job while for workers, by the other side, can be difficult to find an alternative job in the outside sector where to spend their specific skills and where to earn a relatively high wage rate.

Other criticisms arise on the field where human capital theory finds its application. According to Antonelli (2003), a dominant role in human capital models is played by:

(i) a static idea of the firm, in which organizational variety and technological change are scarcely taken into account. In a Fordist-Taylorist context (*A-firm*), where the scientific division of labour is oriented at exploiting the economies of scale and where the firm can always find an optimal answer to every issue, the relative skill needs can be easily planned and tend to be stable over time. Conversely, in a more complex environment, like the one represented by the so called Ohnist-Toyotist (*J-firm*) paradigm, characterized by segmented labour markets and higher job competition, workers' competencies, skill needs and wages are the result of collective, long-run, choices aimed at generating cooperation mixed with competition and meritocratic selection;

(ii) a 'top-down' approach of training policy, where homogeneous agencies provide the necessary skills to as much homogeneous consumers and where problems of asymmetric information are not taken into account;
(iii) a scanty weight attributed to institutional change or institutions in general.

Other three interesting aspects deserve our attention. First, human capital theory implicitly assumes that the effect of training on labour productivity is always certain as well as the reliability of the whole production process. Second, human capital theory describes how to reach the optimum amount of training, how to assess and share the relative costs and returns, but nothing about the contents of such training activities. Third, the basic model of Becker argues that, in competitive markets, workers have the right incentives to pay for general training and firms to pay for specific training. Becker also argues that training in specific skills is quite different than training in general skills because workers are not able to benefit from higher productivity when they change job, or because of positive transaction costs. Therefore, firms have the possibility to recoup their investments and are willing to share some of the costs of specific training. As a conclusion there need not to be any market failure in training. The *market* itself makes workers and firms to undertake the right amount of knowledge investments: insufficient investments can only occur due to imperfect financial markets and severe credit constraints. Becker-like contributions, therefore, seriously question the argument in favour of government regulation and interventions in subsidizing training. What the evidence shows, however, is a quite different scenario: firms, especially in countries like Germany, often pay for their employees general training; most skills, instead of being purely firm-specific are industry-specific and thus of a more general type, because there are many firms in the same industry using similar technologies. With compressed wage structures, even when workers are unconstrained, the amount of training may be well below the first-best level of investment and a scope for government intervention arises (Acemoglu and Pischke, 1998).

The following sections of the paper follow the criticisms described above and introduce three extensions of the basic human capital model. In section 3.2, the transaction cost model is considered in the seminal version of Hashimoto (1981) and in a variant analysing the role played by institutions in determining the optimum team-oriented amount of specific training; in section 3.3 a model of technology adoption and labour training under uncertainty is shown, and, in section 3.4, a model dealing with innovation, training and asymmetric information is discussed. In section 3.5, then, a short review of macro-economic models dealing with major technologies diffusion, human capital and growth is considered.

3.2. Firm-specific training as a shared investment: the transaction costs extension

A further extension of the specific human capital model that analyzes the nature of the wage contract between the firm and the worker is represented by Hashimoto (1981) who applies the concept of transaction costs to explain the sharing of training costs and benefits between workers and firms. The basic idea behind this model is that, differently from Becker analysis, the existence of positive transaction costs offers the reason for rents sharing between the parties: both the employer can dismiss the worker or the worker can quit the current job. In order to minimize the loss from a separation, the parties determine the optimum sharing prior to undertaking the investment.

Consider a two-period model where the parties are both risk-neutral ad the markets are perfectly competitive. Suppose in addition that employment in a given firm entails investment in firm-specific human capital in the first period. Let s be specific capital and g general capital. The specific training cost function is given by

$$c = c(s), \text{ with } c' > 0 \text{ and } c'' > 0 . \tag{10}$$

The equation below, instead, represents the productivity of a trained worker, as a function of general and specific human capital:

$$\pi = g + m \cdot s \tag{11}$$

where m is the value of product per unit of s.

The return to investment in specific training is thus given by the difference between the value of the productivity per unit of s and the value of productivity per unit of initial g, the latter being:

$$y = g . \tag{12}$$

Therefore we have:

$$R = \pi - y = m \cdot s . \tag{13}$$

Suppose in the second period all the relevant facts become common knowledge and the parties decide whether to separate or not. As in Becker analysis, the second-period wage rate earned by workers is determined following the sharing rule:

$$w = y + \alpha R, \quad \text{with } 0 \le \alpha \le 1 \tag{14}$$

while the employer gain, i.e. the return to capital, is given by:

$$r = \pi - w = (1 - \alpha)R . \tag{15}$$

If $\alpha = 0$ then $w = y$, the representative worker is indifferent given the choice of separation while the employer is not. If $\alpha = 1$, instead, $r = 0$ and the employer is indifferent given the choice of separation while the worker is not. In both cases, one of the two parties take the correct decision for both parties. If $0 \le \alpha \le 1$, both parties have the incentive to separate only if $\pi < y$. Therefore, the value of α is irrelevant to the separation decision because the parties are assumed to transact costlessly on the values of π and y. This implication, with zero costs of transacting the assignment of property rights to the investment returns, is nothing more than a statement of the Coase theorem. The sharing outcome comes from the existence of post-investment transaction costs of evaluating and agreeing on the values of π and y, such costs being an important source of uncertainty about the capturability of returns. In order to show the notion of such costs, Hashimoto supposes that the value per unit of specific human capital in the firm is given by $(m + \eta)$, where m is now the expected value of the real productivity and η is a random component with a density function $\phi(\eta)$, with $E(\eta) = 0$, so that $E(m + \eta) = m$. Let ε be the value of specific capital in the alternative employment, where $E(\varepsilon) = 0$ and density function $\psi(\eta)$. The realized values of η and ε represent errors in predicting market conditions facing the firm and the alternative employment, errors in predicting the capacity of the worker to learn new skills on the job, or the influence of real shocks in the economy. For the seek of simplicity, assume also $Cov\ (\eta,\ \varepsilon) = 0$. Fluctuations caused by η and ε are assumed to be known by the respective parties, but are not profitable to negotiate because of high transaction costs involved in curbing the suspicion that one agent is trying to appropriate a portion of the other agent's return. If only the employer can react to the actual value of η, and only the worker can react to the actual value of ε, then we can define:

$\hat{\pi} = g + (m + \eta) \cdot s = \pi + \eta \cdot s$ = actual value of the worker to the firm, and

$\hat{y} = g + \varepsilon \cdot s$ = actual value of alternative employment to the worker.

Using the above two equations, it is possible to determine the jointly optimal separation value:

$$\hat{\pi} - \hat{y} \le 0 \text{, that is } m \le (\varepsilon - \eta) . \tag{16}$$

It is important to note that the rule represented in (16) applies only if the parties can transact without any cost. The worker has the incentive to quit when $w - \hat{y} \le 0$, that is when

$$\varepsilon \ge \alpha \cdot m \equiv \varepsilon^* , \tag{17}$$

while the employer has the incentive to dismiss the employee when $\hat{r} \le 0$, that is when

$$y + \eta \cdot s - w \le 0, \text{ or } \eta \le -(1 - \alpha) \cdot m \equiv \eta^* . \tag{18}$$

From the above it can be seen that, where η and ε are both positive, separation occurs too often with respect to the optimum; the result is that the separation rule $m \le (\varepsilon - \eta)$ is not in general satisfied. Finally, the worker's and employer's gain can be combined, assuming a Nash bargaining outcome, so that returns and costs to training are shared by both the parties. The analysis by Hashimoto reveals that whether or not the investment is shared depends on the existence of transaction costs in evaluating and agreeing on the worker's productivity. The conclusion is a direct application of the Coase theorem to the income streams generated by specific human capital. However, no specific reference is made to technology or technological change: the model considers the general case that, in the fist period, for any reason, the firm must invest in specific training.

3.3. The role of uncertainty

The model presented here is adapted from Gander (2002). Starting from the assumption that technology adoption must be accompanied by completely specific employee training, a model of the firm that includes not only technology adoption, but also the uncertainty of the reliability of labour performance in the production process can be considered. Using a labour-augmenter approach, the author defines the impact of technology adoption in terms of efficiency labour units. The uncertainty is then represented by the probability of reliability of worker performance under the new technology. The basic idea is that training increases individual labour productivity, as in the standard human capital model, but the reliability of the whole production process can still be uncertain, so that final output can be randomly variable.

Assuming disembodied technology and no capital inputs, labour in efficiency units can be expressed as:

$$L^* = A(\tau) \cdot L \tag{19}$$

where the function $A(\tau)$ is the augmenter representing technology adoption and the accompanying firm-specific labour training as a function of τ, training costs. Assuming a production function of the form $Y = F(AL, u)$, with u equal to a random variable measuring production reliability, and modelling the probability of reliability of production process as an increasing function of training investments, like $P(\tau)$, the expected profit maximization problem becomes:

$$\max_{L,\tau} E\pi = PR_g(AL) + (1-P)R_b(AL) - wL - \tau \tag{20}$$

where the subscripts g and b refer to revenue R when labour performance is reliable and when it is not respectively. The first-order conditions, after some substitutions, lead to the following relations:

$$\left(\frac{A' \cdot \tau}{A}\right) \cdot wL + (R_g - R_b) \cdot P \cdot \left(\frac{P' \cdot \tau}{P}\right) = \tau \tag{21}$$

$$\gamma + \left(\frac{(R_g - R_b) \cdot P}{wL}\right)\lambda = \frac{\tau}{wL} \ . \tag{22}$$

Expression (21) states that the equilibrium employment L occurs at the point in which the wage rate is equal to the augmented expected marginal revenue product, so that workers receive w but higher employment reflects the effect of augmentation. In equilibrium, equation (22) instead, shows how it is possible to find the optimum amount of training costs, as the sum of two elasticities: η, the investment elasticity of augmentation, that is $(\tau A'/A)$ and γ, the jointly determined investment elasticity of the reliability probability, $(\tau P'/P)$. The right hand side of (22) is the ratio reflecting the intensity of investment on training and technology adoption with respect to total wage bill.

3.4. Adverse selection and heterogeneous abilities in adopting new technology

In this section I am connected with the criticism imputing to human capital theory the lack of any consideration of asymmetric information in the labour market. The literature dealing with this issue is huge. In particular, adverse selection models of the labour markets (Stiglitz, 1976; Weiss, 1980; Katz and Murphy, 1992) primarily provide a rationale for efficiency wage payments. If highly-educated workers have higher reservation wages, and the quality of each worker is not perfectly observable by the entrepreneur, firms offering high wages raise the average quality of their applicants. The most interesting result is that the optimum wage strategy for firms minimizing costs per efficiency labour unit is to offer a wage rate above the market clearing level.

However, the main gap of these models is that none of them analyzes the effects of technical change on the labour market. Since the seminal contribution of Nelson and Phelps (1966), it is well known that technological change, by introducing new jobs or tasks, affects wages and unemployment through its impact on the relative demand for different categories of labour services. In particular, if more-educated individuals have a comparative advantage in learning how to effectively perform new functions, then technical change will increase the relative demand for more-educated workers (skill-biased technical change).

If we recognize that educational attainment is not the only feature that enhances workers' ability to learn and implement new technologies, but we stress the importance of other, *unobservable*, characteristics, then we face a problem of adverse selection. In fact, workers with the same educational attainment who differ in their ability to adopt new technologies: technical change, through on-the-job training, affects relative demand for workers with both higher observed and higher unobserved ability. However, while the former type of ability constitutes common knowledge between the firm and the applicant, the latter type is known only by workers.

The only model dealing with asymmetric information on the ability level of the workforce, technology adoption and on-the-job training is the one by Kalaitzidakis (1997), who matches the literature on adverse selection in the labour market with models of firm-specific human capital (Becker, 1964, Hashimoto, 1981). In his article he presents a general equilibrium adverse selection model of the labour market in which workers heterogeneity arises in that workers differ in their ability to implement new technologies. Exogenous firm-specific process innovations require forms to teach workers the new firm-specific skills introduced by the new technology. Firms can access workers only by their observed ability, as proxied by their educational attainment, while only workers know their own ability, as the sum of observed and unobserved components.

The role of technological innovation is the following: in altering the production process, an innovation requires workers with new firm-specific skills, and, thus, obliges firms to train workers on the job. As firm's training costs negatively depend on the expected ability of their labour force and positively on their technological level, firms will seek to hire applicants with a higher capacity to learn at least cost.

The main result of the model, however, concerns not much the volume or the content of training, but the justification, in terms of human capital accumulation, of the skill-biased nature of technological change and the rising wage inequality within groups of similar workers, here in terms of educational attainment. What the author shows, in fact, is that more technologically advanced firms pay higher wages to workers with the same level of education than less advanced firms, because they want to attract workers with higher unobserved ability. So, even in the presence of excess labour supply, wages do not fall to clear the labour market because wages are chosen to minimize the average efficiency cost of the firm.

As far as it is concerned, the model provides an explanation for the empirical fact that the increasing wage inequality within groups of workers with the same level of education since the 1970s is mainly attributed to firm-specific shifts in labour demand. The hours of on-the-job training are not formally modelled, but they are assumed to be the tool allowing workers, whose skills completely depreciated cause of the arrival of a new technology, to re-adapt to the new production process.

3.5. Technology adoption, human capital and growth

Human capital theory, and in particular the prescription on the positive relationship between skills accumulation and labour productivity, constitutes the microeconomic pillar for those macroeconomic models studying how economies react to the arrival of new major technologies. The literature presented in this section aims at answering the main research question of the article: to what extent the successful adoption of new technologies by firms affects the growth performance of macroeconomic systems? On this purpose, a literature on general purpose technologies (GPT) has emerged in recent years examining the channels through which the arrival and implementation of a new major technology affects the economy. If the great part of this literature looks at mechanisms like secondary innovations, diffusion, and social learning, there are some contributions studying the interplay between technological change and human capital, in terms of experience and training, or skill specific rather than general education. The models presented here are mainly part of the literature on creative destruction and skills obsolescence as responsible of initial productivity slowdowns: Helpman and Rangel (1999) and Krueger and Kumar (2002) and, in general, growth models based on GPT diffusion *à la* Helpman (1998), Helpman and Trajtenberg (1998a, 1998b), Aghion and Howitt (2002) and Weinberg (2005).

Helpman and Rangel (1999) ask how macroeconomic variables like aggregate output cyclically adjust to the arrival of a new major technology and its following adoption by firms. Since historical evidence seems to show that technological change usually produces an initial slowdown, the authors focus on one possible explanation that involving two types of human capital: technology-specific *experience* that individuals acquire mostly by working with a new technology and general knowledge that they get through school *education* and *general training* in the workplace. The key difference between the two concerns not much where they are acquired, but whether the skills are transferable across technologies: while education increases the range of technologies a worker can operate, experience increases productivity associated with a single technology.

In a model in which labour is the only input on production, wages are determined by labour productivity, that, in turn, depends on individual characteristics, new technologies interact with human capital in two ways: when the new technology requires more education, technology-skill complementarity arises; if, conversely, new technologies require less education, the economy faces technology-education substitutability. An example of the former relationship is given by the arrival of computers and ICT, while an example of the latter can be represented by the transition from the artisan shop to the factory in the XIX and early XX century. An important finding of this investigation is that both experience and education plays a distinct role in the adjustment process and that each of them is able to trigger a recession with the arrival of a new technology. Such recessions, in particular, are driven by a twofold effect, that the authors label as *switch* and *entry* effect, the former associated with experience and the latter with schooling. The switch effect, in fact, occurs when experienced workers switch to a new sector, causing a loss of output since specific experience is supposed not to be transferable across sectors. This effect can be positive or negative: it is positive if the new technology is more productive at all levels of experience, while it is negative when inexperienced workers are less productive with the new technology. The sign of the final effect depends crucially on the speed with which experience increases productivity: when it increases significantly faster in the new sector, even very experienced workers in the old sector can find profitable to switch into the new one, opening a scenario in which their productivity losses can be strong enough to create experience-driven recessions even when the new technology is more productive at comparable levels of experience.

On the other side, the entry effect is given by changes on the educational requirement of workers and the relative fraction of the workforce that lays out of the labour market. A negative effect occurs when technology and education are complementary because individuals have to get more education than before operating the new technology: if this is the case, the economy faces a short-run slowdown. A positive effect, instead, occurs in the case of technology-education substitutability, because people can leave the schooling system earlier, thereby increasing the labour force. If this is the case, the economy can suffer a decrease in aggregate output if this positive effect is accompanied by a sufficiently large negative switch effect, due, in turn, to a sufficiently fast speed of learning or to a low level of productivity of inexperienced workers in the new sector.

A related argument is also that skills affect the responsiveness to technical change, for instance in aiding organizational change. In a recent contribution, Aghion and Howitt (2002) argue that technological change is not skill-biased in the sense it raises the demand for technical production skills; rather, it seems to raise more the rewards to *adaptability*. During the introduction of new technologies, unobserved skills like higher ability, reliability or trainability appear to be in increased demand. The authors point to the rise in the within education and age group wage inequality occurring before the rise in between group inequality and their argument is that this reflects the progressive diffusion of general purpose technologies within industries.

In line with this work is also the contribution of Van Zon and Antonietti (2005): the adoption of a new technology requires the firm to train its workforce. The effectiveness of on-the-job training positively depends on the general skills acquired *a-priori* by the trainees, namely their educational attainment. An increase in the rate of technological change seems to shift the training and education portfolio-mix in favour of the latter, reflecting the idea that firms, in order to minimize the innovations' adoption costs, are more willing to hire more-educated and more-adaptable individuals, a result in line with both theoretical (Kalaitzidakis, 1997) and empirical (Bartel and Lichtenberg, 1987) models.

A slightly different conclusion is reached by Weinberg (2005) who studies the relationship between experience and technology adoption and the effect of technological change on experience *premia* from the labour supply side. In contrast to vintage human capital models, new technologies may complement experience and may be adopted first by experienced workers. Measuring new technologies adoption through computer usage, Weinberg finds that the latter increases in experience of less educated workers while decreasing in experience of more educated. Cross-industry earnings regressions also indicate that technological change has favoured experienced workers among high school graduates and young workers among college graduates. Within a structural model of technology adoption and earnings, and in contrast with work emphasizing imperfect transferability of skills across technologies, the estimates indicate also that when workers adopt new (computer) technology, a higher human capital stock with the old (non-computer) technology increases relative productivity with the new technology. In addition, there is some evidence that young workers are abler and more adaptable to technological change.

Finally, Krueger and Kumar (2002) develop a general equilibrium growth model featuring an occupational advantage of general over vocational education, endogenous technology adoption by firms and educational decisions by households. They argue that two economies growing at potential when the rate of technological progress is low can diverge when this rate increases. Their analysis, thus, provides a possible explanation for the growth gap between European Union, whose policies primarily focus on skill-specific education and US, which instead is more oriented to conceptual education.

In their general equilibrium model households obtain either a concept-base, "general" education or a skill-specific, "vocational" education. Even if the former is more costly to obtain, only workers with general education can operate new, risky technologies incorporated into production, whereas vocationally trained workers are more efficient in operating old, established technologies. By embedding the idea of the dynamic advantage of education into a growth setting, the authors jointly model the adoption decision of firms and the decision of individuals to acquire a particular type of education, and analytically characterize the effect of education policy on growth. The main result of their model regards the effect of an increase in the rate of the available technology: in such an event, countries with different education systems that had a comparable growth initially could diverge. In particular, the difference in the growth rate between an economy focusing on vocational education and one focusing on general education increases with the exogenous rate of technology availability: the economy with better general education can more rapidly exploit the new technologies and might be constrained only by their availability.

On the empirical side, this model provides an interesting explanation consistent with the "Eurosclerosis" view by focusing on education policies. In fact, while European education policies that traditionally favoured vocational education may have worked well during the 1960s and 1970s, when technological change was relatively low, they may have contributed to slow growth and increased the EU-US growth gap during the so called 'information age' of the 1980s and 1990s, when new technologies spread at a more rapid pace.

To conclude, this last section has presented the main macroeconomic models dealing with technology adoption and economic growth driven by human capital accumulation. The issue is how the (exogenous) arrival, and the subsequent implementation, of a new technology affects the growth pattern of the economic systems in which the adopting firms operate. The answer varies according to the set-up we consider even if, according to me, a common outcome seems to emerge: the higher weigh, or the higher comparative advantage, that general knowledge, usually acquired through education, has with respect to specific knowledge, usually acquired through workplace training, in ensuring a sufficient degree of adaptability to rapid economic change. This is not to say that on-the-job training is not important: on the contrary, almost all the models stress the fact that it constitutes the only way in order for workers to familiarize with new jobs, new tasks and new processes. However, from a policy perspective, the challenge that technological change launches on households and education institutions concerns the emphasis they need to give on strengthening the knowledge-base of each individual/worker, that is the prerequisite for further technical learning.

4. Non-mainstream approaches

4.1. Microeconomic foundations: on knowledge, skills and learning

The approaches introduced up to now lie on the production-transaction costs dichotomy and on an idea of the firm as directly represented by the production function: production itself is a particular kind of exchange, of inputs for outputs, and the cognitive issues of the firm are strongly stylized (Montresor, 2004). In this context, in fact, knowledge is often associated with the concept of information while learning is considered as a mere process of information acquisition and accumulation.

During the 1980s and through the 1990s a new paradigm emerges that radically contrasts the static context described before: the Japanese firm paradigm (*J-firm*) and its evolution into the firm as a 'learning organization'.

More important than the concept of 'firm' is the different concept of 'knowledge' developed by this new strand of thought, that is primarily represented by evolutionary economics (Nelson and Winter, 1982). The evolutionary perspective has always underlined the role of innovations and technological change as an engine of economic growth. In contrast with the neoclassical conception of the perfectly informed 'representative agent', the heterogeneity between economic agents is now considered as the main source of dynamics, and the focus of the analysis is the process of 'learning' and economic selection. Differently from the mainstream perspective, scholars like Simon first (1955), Richardson (1972) and then Loasby (1996), starting from Alfred Marshall thought, argue that the firm capabilities depend on cognitive frameworks that are limited, context specific and idiosyncratic. Knowledge utilized in the production process is not a mere datum, but it is continuing re-elaborated and improved by different *learning processes*, sometimes localised, sometimes linked to the specific context in which the same knowledge has been produced or used. Learning cannot be considered as an individualistic information-upgrading process, but as a social and organizational process.

Knowledge can be defined as the intellectual and psychological power to derive new general principles and to develop them in the economic field with the help of science, culture and other sources of understanding (Antonelli and De Liso, 2004).

The amount of knowledge available to each agent depends on:

(i) the knowledge present in the system;
(ii) the accumulation of skills in the population and the investments in knowledge itself;
(iii) the level and quality of existing artefacts.

For *skill* we refer to specific capabilities, abilities, credentials experience and beliefs accumulated by humans through education, training, learning and informal practice. *Artefacts*, instead, represent both machines, products and applied knowledge embodied in them.

A lot of economists have faced up this kind of concepts and it is not the aim of this paper to show all the literature or the debates borne during the last century on this topic. The fact to stress is that people, in taking their decisions, everyday face with complexity and uncertainty. The role of knowledge as the leading factor for economic progress has been recognised; Alfred Marshall himself stated that knowledge is "our most powerful engine of production". The problem is that only a few economists coped with the problem of complexity, but, especially after Lucas critique, they built their models on a rational choice base. Rational choice models can explain a world when uncertainty is absent, where all choices are reduced to logical operations. However, nowadays, this fact cannot be accepted anymore: complexity governs the world and non-logical processes are essential.

Loasby's basic foundation for a useful economic theory is that knowledge is incomplete, and this is due to six kind of obstacles:

(i) insufficiency of induction;
(ii) complexity of the universe;
(iii) limits of human cognition;
(iv) exogenous change;
(v) interdependence of individual initiatives;
(vi) conflicting ideas and proposes.

In his view, it becomes fundamental to know and explain why "error is inseparable from all human knowledge", an idea that comes from Karl Popper, who considered all knowledge as *conjectural*.

Going more into detail, it may be helpful to distinguish four kind of knowledge, which may be arranged in a simple two-dimensional matrix (table 1). The first dimension is introduced by Richardson (1972, p. 895) examination of the organisation of industry, through his reference to Ryle's (1949, p. 28) distinction between "*knowledge that*" and "*knowledge how*".

Table 1. A two-dimensions matrix of knowledge

	DIRECT Knowledge	**INDIRECT Knowledge**
Knowledge THAT (know *what* + *why*)	Formal education R&D	Information (news) Imitation
Knowledge HOW (know *when* + *where*)	Vocational Training Apprenticeship Experience	Learning by doing, by using, by interacting Imitation Tacit Knowledge

Knowing that refers to knowledge of facts, relationships and theories, which are the primary matter of formal education and of R&D. It can be divided in *knowing what* and *knowing why*. In other words, it represents what ancient Greeks used to label as *episteme.*

Knowing how, by contrast, is the ability to perform the appropriate actions to achieve a desired result, what in Ancient Greece was called *techne*. It includes skill both in performing and in recognizing *when* and *where* this skill should be applied. Know-how is combined with *know-whom* and, indeed, with know *who knows whom*. It is differentiated and dispersed, and not easily translated into the language of information and control systems. It can often be partially codified, but codification is never complete. As it is possible to note, here the focus is on the nature of knowledge.

The second dimension focuses instead on the relationships between sources and forms of knowledge diffusion. When we refer to *direct knowledge* we mean the subjects we know by ourselves. *Indirect knowledge* is knowing where we can find the relevant one.

Capabilities are know-how in both dimensions. They can be defined as a mix of knowledge, experience, skills and the information needed to the discovery and estimation of future wants, to research, development and design, to the execution and co-ordination of processes of physical transformation, the marketing of goods, and so on (Antonelli and De Liso, 2004, p. 148).

Capabilities are an essential ingredient in order to explain the development of the power to create and increase specific competencies, a relevant dimension of the division of labour. As stated before, these ones are endogenous and idiosyncratic (Loasby, 1998) and a clear-cut distinction between capabilities and the production function has to be made. The growth of knowledge proceeds through the differentiation and dispersion of knowledge itself, and the co-ordination of economic activity should respect the diversity of knowledge-generating systems.

According to the famous American psychologist George A. Kelly, *experience* is made up of the successive construing of events. It is not merely constituted by the succession of events, since a succession of events may be construed in more than one way, so that different people may draw different conclusions from a particular sequence of phenomena.

If 'knowing what' refers to knowledge of facts, 'knowing why' to scientific knowledge, 'knowing who' to social relations, 'knowing how' refers specifically to skills and competences, built by interactions between agents. In particular, *tacit* or *local* knowledge is a fundamental component of the great performance of industrial districts and clusters; it lies in the intelligence, fantasy and ability of men who live together and in the exchange of information, news and work among people. It is tied to memory and personal experience; it can be codified only through long and costly processes of context-experience sharing. Tacit knowledge, as suggested by Becattini and Rullani (1997), is full of dialectical concepts, idioms, idiocies and is able to resist to scale economies of specialized training.

The lesson is that when dealing with innovation, technological change and technology adoption, other forms of human capital assume a relevance next to the codified channels like schooling and training.

On the methodological side, most of the evolutionary studies use simulation techniques in order to analyse complex stochastic dynamics of economic growth, following the seminal contribution of Nelson and Winter (1982). In such a class of models, the learning process is modelled either at the market level where the selection process eliminates those firms that adopt inferior rules, or at the firm level where the firm itself creates and adopts various rules of behaviour. Even if many different and complex techniques - like genetic algorithms, classifiers systems, genetic programming, and complex sciences analyses - have been increasingly utilized by evolutionary economists in modelling learning processes, it is surprising to note that very little attention has been paid to modelling training, as investment in learning, activities (Ballot and Taymaz, 2001).

4.2.Technology adoption, training policies and growth in an evolutionary perspective: genetic algorithms and the MOSES model

The role that training policies play in affecting the performance of firms and, thus, economic growth has been recently investigated also by evolutionary theory. From section 3.5 we have seen how growth theories have recognized the importance of human capital; in particular endogenous growth theory suggests that the accumulation of human capital and/or knowledge, usually in the form of R&D capital, is the main source of sustained growth of GNP per capita. Moreover, the interplay between human capital and R&D plays a crucial role for growth: human capital may increase the ability to innovate, and raise the productivity of an innovation when it is adopted and applied. The level of the stock of human capital determines the flow rate of innovations and, therefore, the growth rates of productivity and output.

Evolutionary economics has always put the emphasis on the role of innovations and technological change as a driver of economic growth. By stressing the heterogeneity between economic agents as a source of dynamics, it analyses the processes of learning and economic selection. If at the microeconomic level we can find various approaches dealing with technology implementation and firm's performance, as the previous section has shown, at the macroeconomic level the models are not so numerous. On the one side there are some growth models inspired by the Schumpeterian ideas, but these models usually do not contain some microeconomic dynamics to be analytically tractable. Therefore, the most part of the evolutionary models are based on simulation techniques in order to study complex stochastic dynamics of economic growth, following the seminal contribution of Nelson and Winter (1982). Genetic algorithms, classifier systems and genetic programming have been increasingly utilized by evolutionary economists in modelling learning processes. However, and surprisingly, these approaches did not pay sufficient attention to modelling training activities.

The first attempt to investigate the role of training and human capital accumulation as a source of innovation and growth is in Ballot and Taymaz (1996) who include it within an evolutionary microsimulation model of firms. Variables like the number of firms, the rate of growth, the rate of investment in training and education, and the rate of technological progress are endogenous; firms learn about global technology by experimentation, innovation and imitation. They are also allowed to choose different levels of general and specific knowledge and training.

Microsimulation methods appear to be suitable tools in order to model theories within the Schumpeterian paradigm. Microsimulation, in fact, allows for the diversity of the firm's behaviour in areas such as human capital stock, training costs, learning and performance. At this stage, the Model Of the Swedish Economic System (MOSES, see Eliasson, 1977) is used and extended for two reason: first, it is one of the very few microsimulation models based on decision algorithms at the firm level; second, it is a model of a complete economy, so that indirect effects are accounted for. The contributions by Ballot and Taymaz considered here (1996, 2001) add a detailed training-innovation block to the original MOSES model in order to investigate the aggregate effects of training-innovation theory in a Schumpeterian competition framework. The basic idea is that firms that successfully introduce an innovation obtain a quasi-rent, but they need trained workers at the time of implementation of the new technology. It can then be rational for firms to pay for general training, even if in presence of labour turnover. Firms recoup the cost of the investment and the cost of higher wages with the quasi-rent. Specific human capital is supposed to be necessary for applying a technology-specific skill and to be a factor of production. It is lost if a worker quits, so that hiring a worker means that he arrives with zero specific skills. It is acquired through training sponsored by the firm and it allows some learning-by-doing to take place. General human capital instead is transferable, facilitates the learning of skills, and it is not considered as a direct factor of production. It s main role is twofold: on the one side it constitutes a determinant of the firm's 'absorptive capacity1 (Cohen and Levinthal, 1990); on the other, and more important for my purpose, it allows firms to implement new technologies.

In the MOSES model the economy is very complex and characterized by continuous innovation and by a process of creative destruction of heterogeneous skills, jobs and firms. The pace and the rhythm of innovation and the evolution of market structures generate uncertainty that, in turn, generates uncertainty in other firms. Uncertainty is somehow endogenous and there is a kind of uncertainty multiplier.

Agents are supposed to be *adaptive*, in the sense they compensate for limitations of their information by learning continuously. Such an adaptive behaviour, also called *bounded rationality* after Simon, is translated in the model through the use of *genetic algorithms* (GA). The idea of this type of algorithm has been invented by Holland (1975) in order to identify an optimum in the environment in which an agent does not have any information and in which the objective function is very complex. Very sketchy, a genetic algorithm is a tool or a search model based on genetic processes and on the principles of natural evolution (Dawid, 1999). Its basic technique is the following: a population of strings is considered where each string encodes an admissible input of the surrounding system. Every input, in turn, can be a solution of an optimization problem, or the decision rule of an economic agent, and gets some reward from the surrounding system, the so called fitness value of the string. Using these fitness values a new population of strings is generated by applying some genetic operators to the old population. Finally, starting with a randomly initialized population this iteration is carried out for a given number of periods.

In this context, the GA is used to search for more efficient technologies, with the objective of getting closer to the most efficient one. This latter technology, however, remains unknown. The efficiency of search is determined by the level of the general knowledge of the firm and hence affected by its expenditure on general training. This level also influences the capacity to adopt the technologies of other firms. Firms use GA to discover the global technology. A firm has a memory to retain k-number of alternative technology sets at a time and actually uses the set having the highest degree of correspondence with global technologies. Firms learn about the global technology by recombining their own technology sets (*experimentation*), by recombining their sets with other firms' sets (*imitation*), or by mutations (*innovation*). Selection, instead, takes place at the sectoral level through the selection of firms and the action of competition process in the market.

Training in a firm creates a twofold asset: general knowledge and firm-specific skills. While the former is transferable, the latter is not but plays a critical role in the application of what is learnt about the global technology.

Up to now we have looked at the micro-decisions; how the micro-decisions of a population of firms interact to yield aggregate relations? MOSES is a micro to macro model and one of the very few containing some learning by firms through GA. It appears as a basic artificial economy, or a *complex adaptive system*, namely a network of interacting agents, exhibiting a dynamic, aggregate behaviour; and its aggregate behaviour can be described without detailed knowledge f the behaviour of the individual agents. The most interesting property of complex adaptive systems the self-organized nature of the economy. The model, in fact, is characterized by a complex set of interactions between training, knowledge, innovation, diffusion and market structure which determine some self-organizing aggregate patterns. Through their mediation, patterns finally depend on the more stable cultural and institutional environment, and on the history of the economy. According to Ballot and Taymaz (1996), MOSES provides a richer story about the determinants of growth than endogenous growth models because, for the first time, it adds the endogenous creation of competencies to innovation and dynamic competition in markets.

Going a little into details, MOSES is a micro to macro model constructed primarily to analyse the industrial development. Therefore, manufacturing is modelled in greater detail than the other sectors. The manufacturing industry is further divided in four sectors: raw materials processing, intermediate goods, durable and capital goods, consumer non-durables. Each industry consists of a number of firms. Other sectors and the household sector are modelled at the macro level within a Leontieff-type input-output structure. Learning and training, not explicitly modelled in the original version, are included by Ballot and Taymaz (1996). Y means of a set of simulation experiments, the authors reach the following conclusions:

(i) investments in training, if high at the beginning, create a virtuous cycle with strong innovation and growth. In return, growth creates the monetary resources necessary to finance the growth of training;
(ii) non-cooperation by firms yields general and specific training expenditures less than the optimum;
(iii) the type of training matters: a certain balance between general and specific training is necessary.

In a recent contribution, Ballot and Taymaz (2001) extend the MOSES model in order to analyse the impact of three alternative training policies on macroeconomic performance. The first policy is to subsidise all education and training activities. The second policy requires firms to spend a certain percentage of the wage bill on training activities. The third policy the government subsidises training activities if the firm hires unemployed people. Again, the usual distinction between general and specific human capital is made. The former has three indirect effects on productivity: first, it favours the discovery of new technologies; second, it enables it the firm to imitate and even improve the technologies of other firms; third, it increases the productivity of the training investment necessary to acquire specific human capital. The latter, instead, directly improves the efficiency of production.

The interesting conclusions the authors reach after a set of 101 simulations over 50 years are the following:

(i) the timing of the training subsidy is important for fostering growth: in fact, training should become before a major technological change or early during that change;

(ii) the subsidy should not focus on a particular type of training but cover both general and specific training since they are complementary factors for growth.

These models constitute a preliminary effort in the field of microsimulation and public policy. Even if much work is still needed, their potential in providing a complete framework and good policy prescriptions is very high.

5. Summary and concluding remarks

This article shows how the issue of technology adoption and firm-specific skills training has been treated by the specialized economic literature. The main issue is how and to what extent the exogenous arrival and successive implementation of a new technology affects, first the firm's performance and, second, the growth patterns of the economic system in which this firm operates. The first step of the analysis is to identify what kind of skills a firm needs to train after the introduction of a new technology: on this field, the literature clearly distinguishes between *managerial* and *workers' technical* skills, the former being related with the capability to oversee the effectiveness of production processes, and to solve such problems related with supervision, control and incentive building, whereas the latter identifying the technical, practical abilities to solve problems intinately linked to the production process.

The paper distinguishes between two broad approaches: a 'mainstream' approach, which implicitly or explicitly adopts a static view of the firm and a 'Walrasian' idea of skills, and a 'non-mainstream' approach focused on *J-type* paradigm, a Schumpeterian view of the firm and of the market, and a complex, evolutionary idea of knowledge and skills.

Within the former class of models, human capital theory is undoubtely the most prominent approach. Following the basic set-up, specific training due to technology adoption is considered as a special case of firm-specific training for whatever reason. Assuming a relatively stable and static environment, in which the firm's needs can be easily identified and planned, technological change and organizational variety are not explicitly taken into account, the main results "crown" the market as the best institution for optimum training provisions. Since technical skills are not transferable, the entrepreneur somehow engaged in labour trainig activities is willing to bear investment costs up to the point in which the supply of human capital will meet the relative demand, that is where the wage rate will be equal to the marginal productivity of labour. However, the uncertainty about the post-training behaviour of both the firm and the worker is an incentive for the firm not to bear the full costs of training, so that an optimum sharing outcome can be assessed.

A first extension of human capital model identifies in the presence of positive transaction costs, rather than in the uncertainty, the main cause of training costs sharing. The basic contribution by Hashimoto (1981) argues that whether or not human capital investment is shared depends on the existence of transaction costs in evaluating and agreeing on the worker's productivities, a result that is considered to be a direct application of the Coase theorem to the income streams generated by specific human capital investemnts.

Uncertainty can characterize not only post-training behaviour of each party, but also the reliability of labour performance in the production process. This other extension is examined by Gander (2002) who argues that the optimum amount of training costs for adopting new technologies is given by the sum of two elasticities: the investment elasticity of labour productivity augmentation and the investment elasticity of reliability probability.

The association of the firm to the production function allows to pass from a micro to a macroeconomic perspective without a loss of generality. Models of general purpose technologies (GPT) diffusion deal with the issue of how the economies react to the arrival of a new major technology. The main contribution these models bring to the economic debate concerns the explanation of the initial productivity slow-down that usually occurs after the introduction of these technologies, the cause being principally the time and the resources firms spend in order to make their workforce to acquire the necessary specific skills and techniques.

For what concerns the role of asymmetric information, the paper considers the model by Kalaitzidakis (1997), who develops a general equilibrium adverse selection model of the labour market in which workers heterogeneity arises in that they differ in their observed and unobserved ability to implement new technologies. What the author shows is that more technologically advanced firms pay higher wages to workers with the same level of education than less advanced firms, because they want to attract workers with higher unobserved ability. So, even in the presence of excess labour supply, wages do not fall to clear the labour market because wages are chosen to minimize the average efficiency cost of the firm. Indeed, the model provides an explanation for the increasing wage inequality within groups of workers with the same level of education since the 1970s as mainly due to firm-specific shifts in labour demand.

On the other front, what characterizes 'non-mainstream' approaches is a different theorization of what the nature of the firm and knowledge is. In particular, when dealing with technology adoption, the idea of the firm as a set of resources, capabilities and competencies, together with a structural idea of knowledge seem to represent the most diffused paradigm. On the macroeconomic side, evolutionary economics do not seem to provide such an ample variety of models. The only, and quite recent, attempt to analyse how firms' training patterns due to the arrival of a new technology affect the growth performance of economic systems is the research line of Ballot and Taymaz (1996, 2001), who utilize the MOSES model previously developed by Eliasson (1977). MOSES is a micro to macro simulation model of a complex adaptive economy in which the manufacturing system dominates. By modelling the innovation and technology diffusion processes and by making firms learning the new technology through genetic algorithms, the two scholars reach interesting results in terms of training policy and growth.

A final consideration concerns the lacks and merits of these different classes of models. According to my view, mainstream models' strength still lies in their prescriptive capacity and the possibility to be easily interpreted by means of *ad hoc* formalizations. Human capital theory and its extensions are still considered the main benchmark for human capital analyses, even if it considers the context within which the firm operates as completely exogenous. On the other side, non-mainstream models recently borne around the new theories of the firm appear to be very attractive and powerful in investigating all the components of the 'production environment', including its evolutionary paths. Technology adoption, in addition, is not simply a top-down process where workers' are supposed to be the only technology users, but also a bottom-up process, in which workers drive innovations. According to me, what these approaches miss is a clear, formalized and overall accepted theory of education and training as means of investment in learning. However, if the new methodology based on micro to macro simulation will improve and spread, I think it will constitute a very fitting tool not only for the interpretation of actual events, but also for policy prescriptions.

6. References

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