Chapter 3
Technological Change and Human Capital: Conceptual Framework, Theoretical and Empirical Literature

Abstract This chapter presents the conceptual and theoretical framework and theoretical and empirical literature that emphasize the positive growth effects of human capital, technological progress and innovation in increasing and sustaining economic growth. We explain that the major difference arise because the exogenous growth theories perceive technical progress and human capital as exogenous variables in growth accounting model, whereas the endogenous growth theory envisages technical progress and human capital as endogenous variables determining the rates and differences of economic growth across countries. We illustrate that the inclusion of human capital and technological change in growth accounting models motivate endogenous growth literature to provide several interesting explanations of the relationship between human capital and technical change. In particular, it stimulates considerable debate about the complementary relationship between human capital and technical progress, skilled biased technical change, the role of technical progress in skill upgrading and the role of skill and improvement in the accumulation of human capital in skill upgrading. Finally, we show the advantages and limitations of several measures of technological change and human capital that have been used in theoretical and empirical literature; some of these measures are used in our analysis.

3.1 Introduction

Technical progress has been essential for the creation, determination, acceleration and improvement of both quantitative and qualitative aspects of economic growth and welfare in any society. Economic growth theories often emphasize the importance of science and technology and the role of technological change in increasing, improving and sustaining the marginal productivity of capital accumulation and the per capita growth rate of the economy. The crucial role of technological change in economic growth has long received particular recognition amongst economists of different schools of thought, from classical, neoclassical, Schumpeterian,

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evolutionary to new growth theories. However, despite this consonance, both classical and neo-classical economic growth theories view technical progress as an exogenous or unexplained variable. The new growth or endogenous growth theory endogenizes technological progress in economic growth model and explicitly mentions technological progress as the main endogenous factor behind economic growth. Ever since, economists highlight the endogenous role of technical progress in stimulating economic growth and human welfare and identify industrial innovation as the engine of growth (Romer 1990; Freeman and Soete 1997).

Moreover, economic growth literature equally recognizes human capital as an important element for economic growth, and many recent theoretical and empirical studies conducted across countries include some proxies for human capital and emphasize the role of investment in human capital, particularly in the form of education. A higher educational attainment implies more skilled and more productive workers, who in turn contribute to enhancing innovative activities and absorption of advanced technologies. Endogenous growth literature explicitly reveals human capital as one major source of economic growth and acknowledges the endogenous role of human capital accumulation in economic growth. More recent literature finds that various measures of schooling are important determinants of per capita growth: an increase in the quantity of human capital per person leads to higher rates of investment in human capital, and so to higher per capita growth.

In light of this background and the findings in Chap. 2 above, it is therefore reasonable to highlight the need for improvement of education, skill upgrading and technological progress for economic development in the Sudan. Before starting the empirical analysis, it is useful in this chapter to briefly explain the concepts, measures and theoretical and empirical literature in relation to human capital (education), technological change and economic growth. We provide a background for the empirical analysis in the following chapters by surveying the theoretical and empirical literature that emphasizes the positive endogenous growth effects of technical change and human capital in increasing and sustaining economic growth.

The rest of this chapter is organized as follows: in Sect. 3.2 we define the concepts of technological change and human capital; the theoretical and empirical literature on the relationship between technological change, human capital and economic growth are presented in Sect. 3.3. Section 3.4 describes the measures of technological change and human capital; Section 3.5 discusses the role of public policies in supporting endogenous growth, and finally, Sect. 3.6 concludes.

3.2 Conceptual Framework: Technological Change and Human Capital

Before presenting the theoretical and empirical literature, it is useful to begin with the definition of the concepts of technological change and human capital.

Distinction has been made between the term technology, technological change and the effect of technological change. The term technology refers to the branch of knowledge concerned with applied sciences and means the systematic treatment, study, use and application of scientific knowledge for practical purposes, such as in industry. Freeman and Soete (1997) define technology as a body of knowledge about techniques, but frequently used to encompass both the knowledge itself and the tangible embodiment of that knowledge in an operating system using physical production equipment. They use the expression ‘technical innovation’ or simply ‘innovation’ to describe the introduction and spread of new and improved products and processes in the economy and ‘technological innovation’ to describe advances in knowledge.[1]

The rate of technological change is often defined by the rate of increase in the stock of knowledge and relates to the effect it introduces in shifting the production function, leading to either a new shift or an upward shift in the production function. Technological change can be neutral (unbiased) when it does not save any or leads to equal savings of all factors of production, but it can be biased when it results in increased using or saving of one factor rather than others. The classification of technical change into labour (capital) saving technical change implies that it increases the marginal productivity of capital (labour) more than it increases the marginal productivity of labour (capital). Another interpretation indicates that technological change can be equally capital and labour augmenting if it leads to an increase in the production due to either unchanged or equal increases in capital and labour inputs. However, technological change can be purely labour (capital) augmenting, if it leads to increase in effective labour (capital), while effective capital (labour) is constant.

Schumpeter (1934) discusses technological change in the form of innovation including the introduction of new products, services or methods of production; improvement in the quality of existing product or service; development of new markets; exploitation of new sources of supply; and reorganization of methods of operation. Product innovation refers to a substantially new product or an essential improvement to an existing product, while process innovation refers to the introduction of a new or essentially improved method of production.

Human capital refers to health and education that measured by many indicators, for instance, the amount of human capital embodied in people and their respective influence on productivity on the job are determined by skills, ability, education and training (cf. Schultz 1961; Becker 1962). In particular, skill is a broad concept and represents one important form of human capital and tacit knowledge[2]: it refers to acquired and practiced ability or to qualifications needed to perform a job or certain

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[1] See Freeman and Soete (1997: 24).

[2] In distinguishing between codified and tacit knowledge Freeman and Soete (1997) argue: “the codified knowledge implies that knowledge is transformed into information which can either be embodied in new material goods (machines, new consumer goods) or easily transmitted through information infrastructure. While, the tacit knowledge refers to that which cannot easily transferred because it has not been stated or measured in an explicit form, one important kind of tacit knowledge is skill, which can be acquired through learning but often of a non-routine kind” (1997: 404, 405).

tasks competently in the labour market. In addition, other indicators such as training, learning by doing and average years of experience are important components in the formation of skills and human capital.

3.3 Theoretical Framework: Technological Change, Human Capital and Economic Growth

Based on the above framework, in this section we show the theoretical and empirical literature on the relationship between technological change, human capital and economic growth. We explain that economic growth theories recognize and provide different perceptions and analytical frameworks for modelling the various effects of technical change, innovation and human capital on economic growth. The major differences arise because exogenous growth theories perceive and model technical progress and human capital as exogenous variables in growth accounting model, while, in contrast, the endogenous growth theory envisages and models technical progress and human capital as endogenous variables in determining growth process.

3.3.1 Economic Growth Theory and Exogenous Technical Change

The classical economists, starting with Adam Smith (1776), observe the importance of the variable of technical progress in the form of invention (discoveries of new goods and methods of production), innovations, increasing specialization of labour and market expansion in the capitalist system. Despite the apparent recognition of the importance of technical progress in the classical growth theory, technical progress is assumed to remain exogenous variable in growth process.

Next, the neo-classical economists place more emphasis on the significance of technological change. For instance, Solow (1957) attributed 90 % of the US growth rate during the period 1909–1949 to technical progress; Abramovitz (1956), Kenderik (1956) and Solow (1957) attributed almost all the change in output per hour worked in 1950s to technological change. Subsequent analysis by Jorgonson et al. (1987) showed the importance of technological change beside the increase in the effective labour force and the effective stock of capital in generating growth in output per worker. The neoclassical growth theory assumes an aggregate production function exhibiting constant returns in labour and capital; the only source of output growth being the increase of capital stock. While the rate of technological change is assumed exogenous variable, represented as a residual factor to measure the growth of TFP, thus in the absence of technological change diminishing returns will eventually cause all economic growth to cease (cf. Solow 1956, 1957; Swan

1956).[3] Therefore, in order to compensate the diminishing returns of capital in the neo-classical framework long run and sustainable growth rate of output per capita assume to equal the continuous advances in the exogenous rates of technological progress in the form of new goods, new markets or new processes. The major limitation of the neoclassical growth theory is that the long run per capita growth is exogenous and determined entirely by the exogenous technical change or residuals factor, which is determined outside the model. This also called the black box problem since the residuals factor includes technical progress beside the contributions of many other variables such as human capital (education), organization, management, knowledge, new machines, etc. Moreover, although, technical progress is included in the neo-classical model, it is not treated as a production factor like capital and labour, and the effect of technical progress is viewed only as a shift in the production function (cf. Solow 1956, 1957).

3.3.2 Economic Growth Theory and Endogenous Technical Change

The neo-classical growth theory fails to explain persistent differences in growth rates across countries because it considers the rates of technological progress, which entirely determine the growth rate, as an exogenous variable and fails to deal with increasing returns in a dynamic general equilibrium framework.

The endogenous growth theory contributes to improving understanding of the interaction between technological change and economic growth and fills the gap in the neoclassical theory by recognizing the important endogenous effects of technological progress and innovation for creating and sustaining economic growth. In particular, the endogenous growth theory considers an endogenous technological change and innovation within a dynamic general equilibrium framework and avoids diminishing returns to capital. The endogenous growth theory assumes that technical change and human capital are the major sources of endogenous growth and the presence of increasing returns to scale and externalities prevent diminishing returns to accumulation of capital and so guarantee the steady state of growth in the long run.

An earlier attempt of the endogenous growth theory was made by Schumpeter (1934), who assumed that technological progress, innovation and their diffusion are driving forces and at the centre of the dynamics of the economic system. Schumpeter provides a pioneering theory of innovation that forms the basis for

[3] The neo-classical Solow – Swan model assumes a general production function ***Y(t),*** in which the flow of output produced at time ***t*** and there are only two inputs, physical capital ***K(t)***, and labour ***L(t)***, the production function takes the form:

$$Y(t) = F\,(K(t), L(t), t)$$

The growth rate of the production function depends on time ***t***, which reflects the effect of technological change. The long-run growth rate is determined entirely by exogenous elements such as the saving rate and the level of technology.

the subsequent thinking on the dynamic role of technological innovation in economic growth determination. Schumpeter considers innovation as an activity made by one or more workers (e.g. skilled workers), which produces an economic gain, growth and profit either by reducing costs or creating extra income.

A subsequent attempt by Arrow (1962) indicates that technology improvement and the growth of technical change become endogenous due to an unintended effect of learning by doing. Other earlier endogenous growth models represent the major sources of growth by technical progress, which is viewed as a by-product of production and investment in human capital (cf. Uzawa 1965; Nelson and Phelps 1966). Uzawa (1965) interprets technical progress as representing human capital per worker, assuming that its growth required the use of labour services in the form of educational inputs and analyzed optimal growth paths.[4]

Further efforts by Nelson and Winter (1977, 1982) attempt a search for a useful theory of innovation, and present an evolutionary theory of economic change that assumes economic change partially stems from innovation on the part of the firm. The ensuing attempt by Dosi et al. (1988) contributes to an evolutionary theory of endogenous technical change by investigating the interaction between technical change and economic theory.

Since the mid 1980s, starting with the work of Romer (1986, 1989, 1994), Lucas (1988) and Rebelo (1991), which are based on the work of Arrow (1962) and Uzawa (1965), the endogenous growth theory explicitly recognizes the endogenous role of technical change and distinguishes between labour and human capital. The endogenous growth theory avoids the diminishing returns to the accumulation of capital and highlights the role of increasing returns and assumes that growth may proceed indefinitely due to the presence of human capital and endogenous technical progress. The endogenous growth theory also predicts that, in the long run, economic growth at the aggregate level is determined by endogenous sources of human capital, technical change, learning by doing, spillovers of knowledge, external effect of human capital and R&D.

For instance, Romer (1986) and Lucas (1988) contributed to revitalizing the growth literature using Arrow's (1962) ideas to eliminate the tendency for diminishing returns by assuming that knowledge creation was a side product of investment and a positive effect of experience called learning by doing or learning by investing, but that the rate of technical change remains constant. Next, a major contribution by Romer (1990) presents a pioneering endogenous growth model where technical progress is defined by R&D; assumes that non-homogenous capital consists of a set of different intermediate goods; and new intermediate inputs are discovered when R&D resources are devoted to the search process. Romer (1990) identifies two major sources of increasing returns to capital due to specialization or product differentiation, as in Romer (1987), and research spillovers, in which growth will accelerate indefinitely. Romer (1990) assumes knowledge about technology is a nonrival input and induces spillover effects.

[4] See Aghion and Howitt (1998: 24).

Different from Romer (1990), Aghion and Howitt (1992) present an endogenous growth model that defines technical progress by both R&D and accumulation of technological knowledge through the channel of industrial product and process innovations, which improve the quality of products. Aghion and Howitt's (1990, 1992, 1998) framework differs from earlier models of endogenous growth (Romer 1986, 1990; Lucas 1988) in assuming a model of growth based on Schumpeter's (1942) process of creative-destruction. Where growth results exclusively from technological progress, which has positive and normative implications for growth in creating losses as well as gains, by rendering obsolete skills, goods, markets and manufacturing processes. Innovation consists of 'creative-destructions' rather than just new additions to production, and individual innovations are sufficiently important to affect the entire economy. Aghion and Howitt (1990) follow Romer (1990) in endogenizing technical change in producing endogenous growth, and follow Arrow (1962), Romer (1986) and Lucas (1988) in introducing learning by doing as a second source of growth beside innovation. They assume that the accumulation of learning by doing in the intermediary industry will introduce an increase in productivity in the consumption goods sector, and, in particular, intermediate firms will experience a complete spillover of their learning by doing, which also spills over into the research sector. Different from Romer (1986), the spillover of learning by doing in Aghion and Howitt (1990) leads to private economy growth: they assume that an increase in learning by doing will have a positive direct external effect on the average growth rate. Aghion and Howitt (1992, 1998) assume that a stochastic economic growth is generated by random sequences of product innovations and quality-improving (or vertical) innovations that themselves result from (uncertain) research activities by firms. The average growth rate is determined by the interactions of spillovers or two externalities: positive effect, whereby the knowledge embedded in each innovation can be used by all future researchers to generate growth; and negative effects, namely the business stealing effects.

3.3.3 Human Capital and Economic Growth

Economists have long recognized the importance of human capital to the growth process. For instance, Adam Smith's writings at the beginning of the first industrial revolution recognized that human skills were already becoming more important than raw materials in the designed and manufactured machines. Endogenous growth theory fills the gap in earlier growth theories by assuming the accumulation of human capital is another source of endogenous growth. For instance, both Romer (1986) and Lucas (1988) present endogenous growth models where higher accumulation and an average level of human capital in a context of either increasing or constant returns lead to higher productivity of workers and a higher endogenous growth rate. The endogenous growth theory emphasizes the endogenous role of technology and human capital in economic growth, elaborates on the interaction between them and their central roles in determining the magnitude, speed and difference of growth rates across countries (cf. Abramovitz 1986; Lucas 1988; Romer 1990; Aghion and Howitt 1992). The literature discusses the relationship between human capital and economic growth following the pioneering approaches by Nelson and Phelps (1966) and Lucas (1988) and the contributions of Romer (1986, 1989, 1990) and Aghion and Howitt (1992).

An earlier attempt of the endogenous growth model is the AK model, which assumes a constant return to scale in a broad aggregate capital including physical and human components "K", an improvement in the level of technology, raises the marginal and average product of capital and the growth rate.[5] The AK model has the advantages of inclusion of physical and human capital, elimination of diminishing returns to accumulation of capital and creating endogenous growth; its limitations are the assumption of a fixed level of technology and the failure to explain long run balanced growth rate.

An earlier pioneering approach refers to an important contribution by Nelson and Phelps (1966), which assumes growth rates as being driven by the stock of human capital, which in turn affects a country's ability to innovate or catch up with more advanced countries. Nelson and Phelps (1966) explain differences in growth across countries are primarily due to differences in human capital stocks and the abilities to generate technical progress. They assume that growth is primarily driven by the stock of human capital, but the effects of education and human capital are more important for producing technological change than for producing output under a given technology. Nelson and Phelps (1966) and, more recently, Benhabib and Spiegel (1994) assume that human capital[6] is necessary for innovations (capacity to innovate) and for adapting to new technologies and thereby speeding up technological diffusion throughout the economy. A first implication of the Nelson-Phelps approach is that productivity growth and the rate of innovations should increase with the level of educational attainment, particularly with the enrolment in secondary and higher education, which best reflects the numbers of potential R&D staff in a country. Recent empirical studies verify this result and show the significant impact of secondary and higher educational attainment level on the rate of productivity growth (cf. Barro and Sala-i-Martin 1995; Benhabib and Spiegel 1994). A second implication of Nelson and Phelps (1966) is that the marginal productivity of educational attainment is increasing in or with the rate of technological progress (including both innovation rate and speed of adapting to new technologies). Some studies verify this result and find that education induces a significant impact on productivity growth only when it is explicitly related to the rate of innovations and the speed of technological catch-up (cf. Bartel and Lichtenberg 1987; Benhabib and Spiegel 1994). A third interesting result of Nelson and Phelps (1966) is that education should permit the countries falling behind to

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[5] The **AK** production function without diminishing returns and with a fixed level of technology $\boldsymbol{A}$ is defined by: $\boldsymbol{Y} = \boldsymbol{AK}$.

[6] In Nelson and Phelps (1966) approach human capital is referring to education and the highly skilled workers.

learn more from advanced countries and thereby achieve a higher degree of productivity improvement when innovating. Recently, Benhabib and Spiegel (1994) support this result and indicate that the effect of past educational attainment levels on current growth rates is more obvious across countries that fall behind in terms of aggregate productivity, but growth is to be principally driven by technological catch-up. Thus, the inclusion of technical progress beside human capital substantiates the role of human capital in technological catch-up.[7]

A further interesting approach was introduced by Lucas (1988), based on Becker's (1964) theory of human capital, and on the idea that growth is primarily driven by the accumulation of human capital (education).[8] The Lucas (1988) approach is a pioneering contribution to the endogenous growth literature: it regards human capital accumulation as the engine of growth, as an alternative (to technological change) and as a complementary source of sustained growth.[9] Lucas (1988) adapts Uzawa (1965) and Rosen's (1976) formulation and assumes that growth rate is linearly related to human capital level and its accumulation over time. One implication of the Lucas model is that human capital accumulation is a social activity, involving groups of people, in a way that has no counterpart in the accumulation of physical capital. Another implication is that economies with high human capital stock can easily produce more and can thus sustain a high growth rate. On the other hand, an economy beginning with low levels of human and physical capital will remain permanently below an initially better endowed economy.

Hence, in the Lucas model, differences in growth rates across countries are mainly attributable to differences in the rate at which those countries accumulate human capital over time, assuming that the rate of technical progress remains fixed or exogenous, while Nelson and Phelps (1966) explain that differences in growth across countries are primarily due to differences in human capital stocks and the abilities to generate technical progress. Moreover, Lucas (1988) discusses the relationship between productivity growth and the rate of human capital accumulation, whereas Nelson and Phelps (1966) show that productivity growth and the rate of innovations should increase with the level of educational attainment and particularly so with the enrolment in secondary and higher education. Furthermore, Lucas (1988) assumes that the marginal productivity of education is determined and sustained only by the accumulation of human capital, while Nelson and Phelps (1966) assume the marginal productivity of educational attainment is increasing in the rate of technological progress (including both innovation rate and speed of adapting to new technologies).[10]

[7] See Aghion and Howitt (1998): 339, 340.

[8] Lucas (1988) defines human capital as general human skills that are produced and acquired by education.

[9] See Aghion and Howitt (1998: 327).

[10] See Aghion and Howitt (1998: 327, 339).

One feature of Lucas' (1988) model is the assumption of constant returns to scale and the accumulation of human capital, which implies that a diminishing return can be avoided when the production function includes both physical and human capital and both these grow at the same rate. Thus, in the steady state, rates of return remain constant and the economy can grow at a constant and sustained rate mainly due to endogenous growth from human capital accumulation, and without the need for external 'engine of growth' or exogenous technological change. Barro and Sala-i-Martin's (1995) results indicate that the presence of human capital (as an alternative to improvements in technology as a mechanism to generate long-term growth) may relax the constraint of diminishing returns to a broad concept of capital and can lead thereby to long term per capita growth in the absence of exogenous technological progress.

Another interesting feature of Lucas' (1988) model is the introduction of human capital with externalities or spillovers effects of education between individuals. Lucas (1988) distinguishes between the internal effects of human capital, i.e. the effects of an individual's human capital on his own productivity, and the external effects of human capital that contributes to the productivity of all factors of production, including his or her own human capital. The external effects of human capital induce more rapid physical than human capital growth; the average skill level of a group of people is assumed to affect the productivity of each individual within the group. Both Lucas (1988) and Romer (1986) highlight the spillover effects or benefits from aggregate human capital, supposing that human capital can be passed down from generation to the next and can therefore grow without bound. Assuming that this special kind of knowledge is only produced as a side effect of other activities, investment in physical capital or investment in schooling respectively, while Romer (1989, 1990) allows this special kind of knowledge to be produced intentionally and not as a side effect. Azariadis and Drazen (1990) find that the existence of threshold externalities in education technology can lead to several steady state growth paths and explain existing continuous and perpetual differences in growth rates across countries due to unequal initial human capital endowments.[11]

Moreover, Lucas (1988) follows the theory of human capital and distinguishes between two main sources of human capital accumulation (or skill acquisition), namely education and learning by doing. Based on theory of human capital, Lucas assumes that the allocation of time over various activities in the current period affect productivity or affect the accumulation of human capital $h(t)$ level in future periods. Lucas identifies both the way the human capital level affects current production and the way the current time allocation affects the accumulation of human capital. Lucas assumes that a worker with skill level h devotes the fraction of $u(h)$ of his non-leisure time to current production and the remaining $1 - u(h)$ to human capital accumulation. So, the human capital equation in the Lucas model is defined by: $h = h(t)\delta(1 - u(t))$, $\delta > 0$ which spells out how current schooling time

[11] See Aghion and Howitt (1998: 331, 333).

(1 − u) affects the accumulation of human capital. If learning by doing rather than education is the primary source of human capital accumulation, the above equation should be replaced by the following equation: h = δhu.[12]

The subsequent contribution by Romer (1990) presents a growth model of endogenous technical change assuming long run growth is increasing in and driven primarily by both technological change (the accumulation of knowledge) and the stock of human capital[13] rather than the total size of the labour force or the population. He emphasizes the central role of technological change, stock of human capital, externalities and increasing return associated with investments in human capital in the research sector and in determining the rate of growth. He finds that an economy with a larger stock of human capital will experience faster growth. Romer (1990) follows both Romer (1986) and Lucas (1988) in their assumption of external effects arising from knowledge spillover. Romer (1990) assumes that the final output is a function of physical labour, physical capital, human capital and an index of the level of technology. The application of more human capital to research leads to higher rate of production of new designs and stock of knowledge, which increases the productivity of engineers working in the research sector.[14] The output of the design is a linear function of human capital and technology when the other variables are held constant. The marginal productivity of human capital employed in the manufacturing sector grows in proportion to technology. Unlike Lucas (1988), Romer (1990) follows Schumpeter's (1942) assumption that technological change drives growth and provides the incentive for continued capital accumulation, the growth rate is increasing in the stock of human capital. So, both capital accumulation and technological change account for much of the increase in output per worker.

The endogenous growth model proposed by Aghion and Howitt (1992) assumes that capital accumulation includes both physical and human components. They assume that both the average and the variance of the growth rate are increasing functions of the size of innovations, size of skilled labour and the productivity of research, which is measured by the effect of research on the Poisson arrival rate of innovations. They distinguish between three categories of labour: unskilled labour, which can be used only in producing consumption goods; skilled labour, which can be used either in research or in intermediate sector; and specialized labour, which can be used only in research. They assume that skilled labour has two uses: in the manufacture of the latest generation of intermediate goods and research aimed at discovering the next generation of these goods. An expectation of more research in the next period must correspond to an expectation of higher demand for skilled labour in research in the next period. They assume that research produces a random

[12] See Lucas (1988) and Aghion and Howitt (1998: 327, 329).

[13] Romer's (1990) definition of human capital includes activities such as formal education and on the job training.

[14] One implication of Romer's (1990) argument is that, despite having the same amount of human capital, an engineer working at current time has higher productivity than one who worked in the previous century because he acquires the advantages of all additional improvements and accumulation in knowledge since then.

sequence of innovations, and that the Poisson arrival rate of innovations in the economy at any instant is dependant on the current flow of skilled labour used in research. They assume that skilled labour is important factor in research, innovations and economic growth, and that an increase in the endowments of skilled labour increases both the marginal benefit and reduces the marginal costs of research by reducing the wage of skilled labour.

Moreover, several recent empirical studies conducted across countries use many measures of human capital and find that human capital is important determinant of long run economic growth or per capita growth.[15]

3.3.4 The Relationship Between Technological Progress, Human Capital (Skill) and Skill Upgrading

In this section, we show that the inclusion of technological change and human capital in growth accounting models motivates endogenous growth literature to postulate several explanations of the relationship between human capital and technical change. In particular, considerable debate arises around four issues regarding the complementary relationship between human capital and technical progress, skilled biased technical change, the role of technical progress in skill upgrading and the role of skill in skill upgrading.

The first hypothesis highlights the complementary relationship between technological progress and human capital. The interpretation of this hypothesis is that the high educated workers can adapt more and easier to changing technologies than the low educated workers. A large endowment of human capital facilitates the fast adaptation of technologies and induces positive impacts on economic growth, and faster technology driven growth in turn can induce more schooling by raising the rate of return on investment in schooling (cf. Nelson and Phelps 1966; Benhabib and Spiegel 1994). Moreover, human capital or skill is found to be more complementary with technology and capital (cf. Goldin and Katz 1998; Mincer 1989). Because the 'embodiment' of technical change in both physical and human capital indicates that the improvement in their quality implies their complementarity with technological change (Bartel and Lichtenberg 1987). In addition, more innovation stimulates human and physical capital accumulation by raising the marginal product of capital, while more capital accumulation stimulates innovation by raising the profit accruing to innovation (Aghion and Howitt 1998). Furthermore, a high proportion of skilled workers in the labour force implies a large market size for skill-complementary technologies and encourages faster upgrading of the productivity of skilled workers (cf. Acemoglu 1998).

[15] For instance, Rebelo (1991), Barro (1991, 1996), Barro and Lee (1993, 1996, 2000a, b, 2010), Benhabib and Spiegel (1994), Barro and Sala-i-Martin (1995), Mankiw et al. (1992), and Kahn and Lim (1998) all find strong positive correlation between schooling and the growth rate or the subsequent growth rate of per capita GDP or TFP.

Several studies use many different indicators to examine the technological progress and human capital complementary hypothesis. For instance, the increasing utilization of higher educated workers shows positive correlation with TFP growth (cf. Kahn and Lim 1998), with physical capital, capital equipment or capital intensity (cf. Griliches 1969; Bartel and Lichtenberg 1987; Goldin and Katz 1998), with R&D (Acemoglu 1998; Machin and Van Reenen 1998) and with the use of new technologies (cf. Acemoglu 1998), especially ICT (cf. Goldin and Katz 1998; Bresnahan et al. 1999; Autor et al. 1998.

The second hypothesis concerns the skill-biased nature of technical change. The rationale for this argument is that technical change has dual implications on employment and demand for skill, which is found biased against low skilled workers and lead to unemployment /job mismatch (cf. Muysken et al. 2002a; b) or crowding out of low skilled workers (cf. Muysken and ter Weel 1998).

Another interpretation is based on the argument that technical changes induce creative-destruction effects on growth and employment. While it enhances productivity growth, stimulates demand and the creation of new jobs, it also destroys jobs because it is primarily labour saving through automation and skill obsolescence (cf. Aghion and Howitt 1992, 1998).

In the recent literature two features have received particular attention: the first issue is that economic debate has become focused on the significant change in the composition of labour demand, particularly the increase in the demand for skilled workers and sharp decline in the demand for low skilled workers. The second issue is focused on the distributional aspects of technical change, particularly the implications of skill-biased technical change (SBTC) on the structure of employment and wages that has shifted against the low skilled workers, leading to either an increase in unemployment of low skilled workers or increasing wages divergence between high skilled and low skilled workers, which leads to greater inequality (cf. Autor et al. 1998; Acemoglu 1998; Bound and Johnson 1992).

The skill-biased technical change (SBTC) hypothesis has been verified both at the macro level across both developed and developing countries (cf. Berman et al. 1998) and at the micro level within industries (cf. Berman et al. 1994). SBTC is related to various measures of technical changes such as TFP growth (cf. Kahn and Lim 1998), R&D (cf. Berman et al. 1994; Acemoglu 1998; Machin, and Van Reenen 1998) and the use of IT or ICT (cf. Bound and Johnson 1992; Berman et al. 1994; Freeman and Soete 1994; Autor et al. 1998).

The third hypothesis explains the role of technical progress in skill upgrading. The interpretation of this hypothesis is that both the technology-human capital complementarity and skill-biased technical change hypotheses imply that a higher rate of technical progress should bring an increase or upgrading in skill level. Several studies in the literature use many indicators to show the role of technical progress (in the form of TFP, R&D, ICT, IT or computer use, etc.) in skill upgrading. For instance, skill upgrading, defined by the increasing incidence of training, increases with the rate of technological change (cf. Mincer 1989; Bartel and Sicherman 1995, 1999),[16] especially in sectors in which the Jorgenson measure of productivity growth was higher (cf. Lillard and Tan 1986) or showing an increasing use of IT or computers (cf. Bresnahan et al. 1999). Skill upgrading, defined by the shift away from unskilled towards skilled employment or increase in the share of white-collar high skilled workers, is also positively correlated to variables related to technological change, such as R&D investment and growth in the number of patent (cf. Colecchia and Papaconstantinou 1996).[17] In addition, skill upgrading, defined by the increase in the wage share of white collar workers, is positively related to two measures of technology: the level of investment in R&D and computers (cf. Berman et al. 1994). Furthermore, skill upgrading, as defined by the change in the share of educated workers in employment and return to schooling or wage rate, is positively correlated with the increase of R&D intensity (cf. Machin, and Van Reenen 1998). Moreover, skill upgrading, as defined by the share of high skilled workers, is positively correlated with TFP (cf. Garcia Cervero 1997) or the use of computers, IT, ICT or computer-intensive industries (cf. Autor et al. 1998; Bresnahan et al. 1999). Skill upgrading, decreasing motor skills and increasing cognitive skills accompany the diffusion of ICT, mainly through occupational change rather than educational improvement, and are also positively correlated with productivity growth (cf. Hwang 2000).

The fourth hypothesis deals with the role of human capital or skill acquisition in skill upgrading. Along with the debate on the relation between technological change and human capital and the positive effects of human capital/education on productivity and economic growth, theoretical and empirical literature highlight the role of human capital/education in skill upgrading through externalities and learning by doing. Educational attainment is important because skills acquisition from formal schooling lead to improvement in training and learning abilities and increase the accumulation of human capital through experience or "learning by doing", which in turn interact together and lead to improvements in workers productivity (cf. Autor 2000).[18] Theoretical literature highlights the role of human capital or skill in skill upgrading through externalities, spillover and learning by doing (cf. Lucas 1988; Romer 1986, 1989, 1990). In addition, the average human capital tends to grow over time as human capital investments have a positive external effect on the human capital of the later cohorts (Stokey 1991). Moreover, recent empirical literature shows that in the developed countries, particularly across the OECD countries, human capital may accumulate at a faster

[16] Bartel and Sicherman (1995) find that on the job training will increase if technological change increases the productivity of human capital, reduces the costs of training or increases the value of time in training relative to work; and that the training gap between the highly educated and the less educated narrows, on average, as the rate of technological change increases.

[17] Colecchia and Papaconstantinou (1996) find that a 1 % point R&D intensity higher than average at the beginning of 1980s has implied about 20 % higher than average upskilling per year.

[18] Autor (2000) argues that: first, training is more productive and therefore valuable to high ability workers; second, workers have some prior information about their ability that is not initially visible to employers; and, third, firms are able to learn about ability through skills training.

rate with the past intensive use of high skilled workers (cf. Colecchia and Papaconstantinou 1996). Furthermore, empirical literature from the developing countries shows that in Singapore and Korea investment in human capital via the expansion and improvement of education and training systems, particularly the development of tertiary, vocational and technical education, leads to an improvement in the overall skill content or skill upgrading of the working population. This appears from the improvement in the educational attainment – defined by highest qualification attained – and skill levels, the rise in the share of high skilled workers, scientists and engineers and the fall in the share of low skilled workers. In addition, upgrading of the occupational structure has resulted from the large/rising share of the supply of high educated, white-collar and non-production workers and the small/falling share of blue-collar workers.[19]

These findings emphasize the importance of the endogenous effects of technical progress and human capital for enhancing economic growth. In particular, these explanations imply that next to the important endogenous effects of technical progress and human capital in economic growth, the complementary relationships between them and between them and skill upgrading are also important for enhancing economic growth.

3.4 Measurement of Technological Change and Human Capital

While it is admitted that technological progress and human capital are difficult to measure, the theoretical and empirical literature use many indicators to approximate their effects. It will be useful to illustrate the advantages and weakness of these measures in order to select some relevant measures for the empirical analysis in the subsequent chapters.

3.4.1 Measurement of Science and Technology Indicators

In recent years, a new economic system has evolved that is characterised by both globalisation and the rise of information and communication technologies. This has driven the need for development in science and technology (S&T), which has become more than simply an element of economic growth and industrial competitiveness, but is now also essential for improving social development, the quality of

[19] See Cheah (1997), Low (1998) and Cheon (1999). In Singapore, the transfer of foreign technology and foreign skills stimulates the acquisition of knowledge and skills from abroad and induces positive spillover in upgrading the skill of domestic workers. This has been accompanied with technological upgrading to promote mechanization, computerization, automation, etc. In the Republic of Korea, the integration into global economy or exposure to foreign competition leads to skill upgrading of domestic workers in the manufacturing sector. Skill upgrading of domestic skills facilitates the adoption of foreign technologies and technological catching-up with the advanced countries.

life and the global environment. For instance, the high level of economic and social development in today's industrialised countries is largely the result of past intensive investment in S&T; similarly, newly industrialised countries are catching up because of their active development of S&T.

> Access to scientific and technological knowledge and the ability to exploit it are becoming increasingly strategic and decisive for the economic performance of countries and regions in the competitive globalized economy. The 50 leading S&T countries have enjoyed long-term economic growth much higher than the other 130 countries of the rest of the world. Between 1986 and 1994 the average growth rate of this heterogeneous group of countries was around three times greater than that of the rest of the world. The average economic wealth per capita of these 50 countries has grown by 1.1 % per year. On the other hand, the per capita income of the group of 130 countries – which perform less well in education, science and technology – has fallen over the same period by 1.5 % per year. These trends prefigure a new division of the global economy, based on access to knowledge and the ability to exploit it. (Organisation for Economic Co-operation and Development (OECD) 1997: ix)

The S&T system is often defined as consisting of all the institutions and organizations essential to the education of scientific people, for example, research and development (R&D) institutions, professional societies and professional organisations linking individual scientists to each other and to their socio-economic environment. The theoretical and empirical literature identifies the important role that S&T plays in promoting economic growth and development in both developed and developing countries.[20]

More recent literature addresses the contribution to S&T performance of the 'national systems of innovation'; a widely used modern term that reflects the link between technical and institutional innovative development, including S&T (e.g. Lundvall 1992; Nelson 1993). Lundvall says this broad definition includes "all parts and aspects of the economic structure and the institutional set-up affecting learning as well as searching and exploring – the production system, the marketing system and the system of finance present themselves as subsystems in which learning takes place" (Lundvall 1992: 12–13). In addition, Freeman and Soete argue:

> The many national interactions (whether public or private) between various institutions dealing with science and technology as well as with higher education, innovation and technology diffusion in the much broader sense, have become known as 'national systems of innovation'. A clear understanding of such national systemic interactions provides an essential bridge when moving from the micro- to the macro-economics of innovation. It is also essential for comprehending fully the growth dynamics of science and technology and the particularly striking way in which such growth dynamics appear to differ across countries (Freeman and Soete 1997: 291).

All the definitions of the systems of innovation share the view that S&T institutions play a vital role in determining or influencing innovation and development. The literature on S&T development often distinguishes between input

[20] For detailed theoretical and empirical literature and assessment studies, see for instance, Freeman and Soete (1997), Dasgupta and David (1994), Foray (1999), Mytelka (2001), Cooper (1991, 1994), Velho (2004). For earlier analyses of S&T in Arab region, see also Qasem (1998a, b), Zahlan (1999a, b), Fergany (1999), ESCWA (1999a, b), ESCWA-UNESCO (1998a, b).

(resources) and output (performance) indicators. For instance, the European Second Report on S&T Indicators (OECD 1997) discusses numerous traditional input and output indicators for S&T development. The input indicators are generally divided into financial and human resources. First financial resource or input indicator includes "R&D expenditure – the most widely accepted indicator for evaluating and comparing S&T efforts in different countries and regions. In the absence of an average measurement to determine R&D within the economic structure and the needs of each country, political decision-makers use indicators such as the intensity of R&D (measured as a percentage of GDP or per capita), R&D area of performance, and origin of funding; change in public spending on education in relation to GDP. [. . .] In addition to financial resources, human resources are central to research and technological innovation activities". There are also general demographic and human capital indicators, "such as the number of science and technology graduates and the number of scientists and engineers employed in R&D. [. . .] [There are] four major points relating to human capital: demographic trends, the development of public spending on education, the performance of education systems and researchers and engineers active in R&D". Furthermore, "Human resources in science and technology (HRST) are one of the key resources for economic growth, competitiveness and more general social, economic and environmental improvement" (OECD 1997: 5, 58–59). In addition to total population size and proportion of young people, which represent the human resources potential of each country, educational attainment of the labour force and graduation rates, which show the rate at which newly educated graduates are available at the country level to enter the labour force, particularly the scientific and technological qualifications and doctorate levels, including R&D staff numbers, particularly in S&T fields.

Output indicators, on the other hand, "can be classified according to three parameters: economic, technological and scientific. As to economic outputs, many economists view increases in productivity as a major result of technological investment. [. . .] The percentage of high-tech exports in total export figures emerges as a potentially useful means of measurement. [. . .] Clearly not all results are measurable in economic terms. Scientists and engineers often cite the 'learning experience' as one major benefit of engaging in R&D activities. To assess the accumulated knowledge of a given country, its stock of technical knowledge must be quantified. Without doubt, patents and patents applications are the most commonly applied [technological] indicator in this respect and, irrespective of the shortcomings implicit in this approach, they continue to represent a very useful tool". Finally there are direct research outputs or publications, "focusing on the impact of the publication output of a given country or zone and comparing it to the number of publications produced over a certain period of time" (OECD 1997: 79).

3.4.2 Measurement of Technological Change

The literature uses several indicators to measure the role of technical progress in economic growth and particularly distinguishes between input indicators, which include variables such as R&D expenditures and human resources, and output indicators, which comprise variables such as patent, productivity growth, publication, etc. (cf. OECD 1997). A comprehensive approach of technological progress should be based on integration of input and output indicators.

The traditional indicator used in the literature to measure the contribution of technical change in economic progress is represented by total factor productivity (TFP) (cf. Kahn and Lim 1998). It is also known as Solow Residuals, as Solow (1956, 1957) was the one to find that the growth rate of technical progress emerges as the remaining unexplained variable or the residual parameter – defined as the factor of output that can not explained by the input factors.[21] The use of TFP growth measure indicates the high significance of technical progress: for instance, Solow (1957) finds that around 90 % of the growth in US output per worker during the period (1909–1949) was due to the effect of the residual factor, which measures the effect of technical progress. Moreover, Abramovitz (1956), Solow (1957), Kenderik (1961) and Dension (1962) find that about half of the growth of the US economy up to the 1950s was attributed to technical progress measured by TFP. However, the TFP indicator has several drawbacks such as the lack of relevant and adequate data and the inaccuracy and broadness of the concept of TFP, which includes factors other than technological progress such as human capital (education), organization, management, knowledge, new machines, etc. According to Mincer (1989), productivity growth indicates the consequences of technical change, but is not a measure of it; TFP is a useful measure of technological change only if other factors affecting productivity growth are either unimportant or considered in the statistical applications. In addition, TFP growth measure may imply some measurement errors due to business cycles and economies of scale (cf. Mincer 1989: 4).

The major input indicator in measuring scientific and technological progress is often represented by the data relating to R&D expenditures, which have been widely used across the OECD countries due to their consistency and easier computation compared to output indicators in these countries. The R&D expenditure data can be utilized to analyze the comparative development and breakdown of R&D activities according to sector and source of finance. However, R&D expenditure data has several defects: for instance, that the data reflects only the recorded expenditures and the institutionalized aspects of technology aimed at increasing knowledge. It also does not include many activities that contribute to technological knowledge such as design, learning-by-doing, the indirect public spending on R&D, etc. Moreover, R&D data reflects only the effort put into research, and does not reflect the efficiency with which this effort leads to new knowledge, the

[21] Productivity growth is calculated as the differences between the rate of growth of output and (a weighted measure of) the rate of growth of the capital and labour inputs (Mincer 1989), or the differences in growth rates of the social product and the capital and labour production factors.

quality of R&D work undertaken, the quality of the scientists performing the work, the cost of inputs of labour, equipment and materials, etc. Moreover, the definition of R&D expenditure varies substantially across countries and is difficult to measure for a large number of countries, and does not reflect the effects of the international spillover of S&T and variations across countries with respect to R&D performance. In addition, it does not produce immediate results, making it difficult to establish direct relation between R&D performance and indicators of economic growth, because R&D activities lead to knowledge creation, which may lead to improved performance only in the long run.[22]

The major output indicator is defined by the patent indicator, which is utilized in the literature to measure technological capacity and status of a country, sector or company. The literature uses patent data to measure the output of technological activities, to reflect the technological performance over time and across countries, to examine the technological specialization in key sectors of industry and to protect industrial property rights (cf. OECD 1997). The patent indicator is often widely used in the measurement of technological change because it allows for international comparisons over a long period; it provides more accurate and specific analyses by sector and by technology; and allows for more focus on a company, institution and even single inventor or researcher. On the other hand, the patent indicator also has several limitations, such as: a lesser degree of reliability for countries or sectors with a small number of patents; and possible interruptions by reason of having to work with publication rather than priority dates.[23] Further limitations lie in the difficulty in interpreting average annual growth rates per period due to unstable patent numbers at the end of a period, lack of exact measurements and the potential inconsistency between the required and actual measurements, the latter problem admittedly also applicable to other indicators.[24]

Numerous empirical studies use innovation surveys such as the survey of resources (R&D) indicators, survey of direct progress (output) indicators and survey of indirect progress and impact indicators, which can be evaluated by questionnaires to measure technological change. A well-known example of this is the Community Innovation Survey (CIS). Distinction has been made between innovation surveys according to subject and object approaches. The subject approach focuses on the innovator or firm-level innovative activities, identifies both input and output indicators, includes small-scale incremental change, reflects economic indicators and permits for comparisons within industries or inter-firm comparison, but does not allow for comparison between different industries with different outputs. On the other hand, the object approach focuses on significant technological innovations (new product or process) or the objective output of the innovation process, on the technology itself. It allows for an external assessment of the importance of innovation independent of personal judgment and usually

[22] See OECD (1997) Second European Report on Science and Technology Indicators (1997: 37).

[23] The priority date of a patent refers to the date of first filing, whereas the publication date refers to the date on which the patent was published. This leads to a time lag between the priority and publication year. For example, in the European (EPO) system, patents are published 18 months after first application.

[24] See OECD's Second European Report on Science and Technology Indicators (1997: 90, 91).

identified through expert appraisal or through new product announcement in trade journals or other literature. However, it has limitations as it is confined only to major innovations, neglects small incremental innovation and does not include an assessment of the economic significance of innovation.[25]

Some recent studies tend to measure technological change by using an index of use, investment or expenditures on ICT, IT, computers or computer equipment, which are also called the new general purposes technologies. These indicators are relatively easier to calculate and several studies provide strong results when using them to reflect the use and organization of technological innovation (cf. Autor et al. 1998; Bresnahan et al. 1999). However, the utilization of computer use as a measurement of technological progress and innovation may lead to endogenity and measurement problems (cf. Sanders and ter Weel 2000: 26).

For our macro-micro analysis we use R&D, patent and ICT as more relevant measures of technical change at the macro-micro levels. Moreover, at the micro/firm level we use the innovation survey following the subject approach, as it appears more relevant for assessing only small incremental innovation at firm level. Our analysis will not include the object approach since it focuses on big (radical) innovations and seems inappropriate for measuring the small incremental innovations in our case studies in the Sudan. Other measures, such as the TFP measure, are not very relevant for our analysis and will not be included in our study due to a lack of relevant data and information to estimate these at both macro and micro levels. In order to measure these indicators, we will use the available relevant secondary data and information at the macro level and use the firm survey data at the micro level, as we will explain in Chaps. 4 and 6 below.

3.4.3 Measurement of Human Capital (Human Skills)

The most widely used measures of skill in the literature is educational attainment, as measured by the average years of schooling, occupation measure, the share of non-production workers in total employment and the share of non-production workers wages to total wages. In addition, the literature uses other measures of human capital such as school enrolment ratios, adult literacy rates and school quality measures.

School gross and net enrolment ratios reflect current flows of education that accumulates to create the future stocks of human capital and have been used in several studies (cf. Barro 1991; Barro and Lee 1993, 1996).[26] However, they have

[25] See Smith (2000).

[26] The UNESCO definition distinguishes between gross and net enrolment ratios. "Gross enrolment ratio defines the ratio of all persons enrolled in a given level of schooling to the population of the age group that would be enrolled at that level. While, net enrolment ratio modifies the numerator of the gross enrolment ratio to count only the students enrolled within the designated age group i.e. the ratio of students at a given level of schooling in the designated age group to the total population of the same age group. The net enrolment ratios vary between zero and one, whereas the gross enrolment ratios can exceed one" (Barro and Lee 1993: 4). For detailed definition, see also the UNESCO-UIS website: www.uis.unesco.org.

several limitations: for instance, they only measure current flows of schooling and do not reflect the stock of human capital. In addition, they are susceptible to underestimation and overestimation measurement errors[27]: for instance, net enrolment ratios tend to underestimate the actual value of variables on both mortality and migration; gross enrolment ratios introduce errors related to repetition of grades and dropouts, which are widely observed in developing countries. Gross enrolment ratios overestimate the actual value because their calculation are based on annual surveys of educational institutions in each country and reflect registered number of students at the beginning of each school year rather than computing the actual number in attendance. In general, the net enrolment ratio is relatively more appropriate for measuring the accumulation of human capital; however, the gross ratio has been widely used because it is more often available for developing countries.[28]

The adult literacy rates have been frequently used in several studies to estimate the relationship between human capital and economic growth (cf. Barro 1991; Romer 1989). They have an advantage over school enrolment ratios as they reflect the stock of human capital rather than the flow of investment. However, a major problem with adult literacy rates is that they measure only one component of the current stock of human capital or the first stage in the path of human capital formation, but do not reflect the skills that are obtained beyond the most elementary levels of schooling as well as many other important aspects of human capital and various types of technical knowledge, which are important for enhancing labour productivity and economic growth. The use of literacy to measure the stock of human capital implies that education beyond the most elementary level does not contribute significantly to productivity.[29]

The educational attainment or educational level is measured by average years of schooling to reflect the stock of human capital and allow for across countries or international comparison.[30] It has been widely used in the literature (cf. Barro and

[27] Lee and Barro (1997) use an adjusted enrolment ratio to overcome the problems of underestimation in net enrolment ratios and overestimation in gross enrolment ratios.

[28] See Barro and Lee (1993: 4–6).

[29] See Barro and Lee (1993: 6). "The literacy rates have been used in the United Nations Development Programme UNDP, 1990, to construct an index of human capital. Moreover, Barro and Lee (1993) use adult illiteracy rates to proxy for the percentages of adult population who have no school attainment to fill the gap in the availability of census/ survey data" (Barro and Lee 1993: 6, 7). See also the UNESCO-UIS website: www.uis.unesco.org.

[30] The educational attainment is measured by the average years of schooling, which is computed by adding the product of the number of years of schooling times the number of people in each schooling category across school categories, "i.e. defined by the following formula:

$$\textbf{\textit{Average Years of Schooling}} = \Sigma_j \, YR_j . \, H \, Sj$$

Where j is schooling level, YR_j is the number of years of schooling represented by the level j, and H S_j is the fraction of the population for which the jth level is the highest value attained" Barro and Lee (1993: 7). For detailed definition, see also the UNESCO-UIS website: www.uis.unesco.org.

Lee 1993, 1996) as an appropriate and accurate alternative measure to both school enrolment ratios and adult literacy rates. In recent literature, educational attainment is used to reflect the inflows of new school graduates to existing educational stocks across countries (cf. Barro and Lee 2000a, b). The rapid growth in average years of schooling led to double growth in the stock of human capital in the USA (cf. Mulligan and Sala-i-Martin 1995), educational attainment or the average years of schooling has a significant contribution to the growth of total factor productivity (cf. Kahn and Lim 1998). Although the average years of schooling measure is often widely used as the most popular measure of human capital in the new growth literature and comparisons across countries, it has some drawbacks, such as the assumption of constant elasticity of substitution across workers of different group, which implies that always and everywhere workers of each education category are perfect substitutes for workers in other categories. It assumes that productivity differentials among workers with different levels of education are proportional to their years of schooling, that always and everywhere a year of education adds a constant quantity of human capital and delivers the same increase in skill, whether undertaken by a primary pupil or a college student. It implies that always and everywhere a worker with 16 years of schooling is 16 times as productive as worker with 1 year of schooling, irrespective of the wage rate differentials. It does not consider differences in the fields of study and quality of schooling (quality of teachers and education infrastructure) and wage rate across countries. Moreover, the educational attainment does not directly measure the human skills obtained at schools, namely quality of schooling across countries, and it does not reflect the skills and experience gained by individuals after their formal education.[31]

Some studies use schooling quality measure or the quality of educational output to measure the impacts on various dimensions of cognitive skills that affect an individual's productive behaviour, and thereby the quality of the future labour force (cf. Hanushek and Kim 1995; Lee and Barro 1997).[32,33] Although both the quality and the quantity of schooling are important ingredients of human capital, schooling quality measure has several disadvantages as it varies substantially across countries and is difficult to measure for a large number of countries (Lee and Barro 1997: 1).

The occupation measure or classification is based on the definition of employment structure and the relative shares of educated and non-educated workers in total employment. In particular, the ILO International Standards Classification of

[31] See Mulligan and Sala-i-Martin (1995: 2) and Barro and Lee (2000a: 12).

[32] The definition of this measure includes the pupils/teacher ratios, spending per pupil at primary and secondary schools as a percentage of GDP, and also estimates average salaries of primary school teachers to per capita GDP.

[33] Hanushek and Kim (1995) find that cognitive skills are an important component of relevant variations in human capital, reinforcing the attention to school quality found in many countries today. Their results indicate that quality of labour force has a consistent, stable and strong influence on economic growth, the impact of quality indicates that one standard deviation in mathematics and science skills translates into 1 % point in average annual real growth. This growth effect is larger than would be obtained from over eight years in average schooling.

Occupations (ISCO)[34] is a widely used measure for measuring skill composition in the literature (cf. Colecchia and Papaconstantinou 1996; Hwang 2000).[35] According to the ISCO classification, only WCHS is referred to as “high-skilled”, with all other groups regarded as low skilled. The advantage of the occupation measure is that the change in occupational distribution of employment provides more information on the skills required and measures the change in skills structure. But it has the drawback that it does not necessarily take into accounts on the job learning and, in particular, skills associated with the use of new technologies.[36] It also fails to account for the changing nature of skills under an occupational title.[37]

The share of non-production workers to total employment measure is defined by the ratio of the non-production workers to total employment and has been usually used in the literature (cf. Kahn and Lim 1998; Cheon 1999). However, it has several limitations: for instance, it does not exactly reflect change in relative demand for non-production workers, and it may over-represent the shift in demand for non-production workers. Moreover, the definition of non-production workers includes a lot of low-skilled service jobs such as janitors, cleaners or simple clerical jobs, and various liberal occupations, while excluding production supervisors, foremen and skilled workers that are of considerable importance in manufacturing sector of developing countries (Cheon 1999: 12, 13).[38]

The share of non-production workers’ wages in total wages is measured by the ratio of non-production workers wages to total wages, and has been used in several empirical studies (cf. Kahn and Lim 1998). Its advantage is that the changes in the non-production share in the wage bill provide a better measure of the demand shift toward non-production workers, provided that the elasticity of substitution between production and non-production workers is above one (cf. Berman et al. 1994; Cheon 1999). However, it has several limitations: for instance, the measure is originally based on the definition of non-production and production workers for skill and unskilled workers and may suffer the same measurement errors related to the definition of non-production and production workers as we explained above.

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[34] The ILO International Standards Classification of Occupations (ISCO) are aggregated in the following way:

White-Collar high-skilled (WCHS) includes legislators, senior officials, managers, professionals, technicians and associate professionals.

White-Collar low-skilled (WCLS) includes clerks, services workers, shop and market sales workers.

Blue-Collar high-skilled (BCHS) includes skilled agricultural and fishery workers, craft and related trade workers.

Blue-Collar low-skilled (BCLS) includes plant and machine operators and assemblers and elementary occupations.

[35] Hwang (2000) finds that skill upgrading, decreasing motor skills and increasing cognitive skills are accompanying the diffusion of ICT, mainly through occupational change rather than educational improvement.

[36] See Colecchia and Papaconstantinou (1996: 8).

[37] See ILO (1998) World Employment Report (1998/1999: 35).

[38] See Kahn and Lim (1998) and Cheon (1999: 12, 13).

Moreover, the wage measure is applicable only when the elasticity of substitution between production and non-production worker is above one. Furthermore, it may be inaccurate to reflect the movement in the stock of human capital when the relative wages change for reasons other than changes in human capital and technological stocks (e.g. due to price change). So, the wage measures may induce some measurement errors (cf. Cheon 1999; Goldin and Katz 1998; Machin and Van Reenen 1998).[39]

For our analysis at the macro level we use the measures of school enrolment ratios, literacy rates, educational attainment, school quality measures and occupational classification to assess skill levels, based on information and data from many relevant sources (e.g. Sudan central bureau of statistics population census data for 2008, the UNESCO, UNDP, etc.). In addition, in our analysis at the micro/firm level, we use two more relevant measures of skill, namely, educational attainment and occupational classification, based on data obtained from the firm survey as we will explain in Chaps. 4, 5 and 6. Our analysis will not include other indicators such as the share of non-production workers in total employment and the share of non-production workers wages in total wages due to a lack of relevant data to estimate these. Instead, we use the share of high-skilled in total employment and the share of high-skilled wages to low-skilled wages according to education and occupation definitions.

3.5 Endogenous Growth and Public Policy

We mentioned in Sect. 3.3 that endogenous growth literature revealed several robust facts and interesting implications that paved the way for growth; it is convenient in this section to explain that it also provided some insights for a possible role for government policy. We explain below the literature and arguments for government intervention to promote the accumulation of technology, human capital and hence growth rate.

The most popular view in the literature is that the rationale for government intervention is basically related to the idea that knowledge (in the form of technical progress or accumulation of human capital) is a public good, which is non-rival and partially excludable. As in Romer (1990) and Barro and Sala-i-Martin (1995), these two features imply an unbounded growth and incomplete appropriability of knowledge and raise the possibility of knowledge spillovers across firms and hence the whole economy. While the feature of spillovers of knowledge supports endogenous growth, it also creates a form of externality and implies that private investments generate a positive external effect and the private returns from investment tend to be lower than the social returns. The outcomes tend not to be Pareto optimal but sub optimal and require government intervention to correct the distortion. The social

[39] See Cheon (1999: 12, 13), Goldin and Katz (1998) and Machin and Van Reenen (1998).

optimum can be achieved by many instruments such as providing subsidies (which can be financed by taxation) to improve the accumulation of technology and human capital, incentives and returns from investment for private investors.

In the endogenous growth literature some studies explicitly model the importance of technology and human capital for endogenous growth, but only implicitly indicate a role for public policy. For instance, while the Lucas (1988) model emphasizes investment in human capital, it only implicitly allows for a role for public policy through subsidies (Haslinger and Ziesemer 1996: 230). Moreover, the Arrow (1962) learning-by-doing and Romer (1986) models imply an indirect intervention: an investment tax credit that increased the accumulation of capital necessarily also increased the accumulation of technology (Romer 1990: S94).

According to Ziesemer's (1987) interpretation, T. W. Schultz (1964) presents a pioneering theoretical justification for a central role for government interference to promote public investment and emphasis their long-run effects on growth and development. Schultz's (1964) theory reveals that the provision of public factors, such as basic education and basic scientific research, is necessary for human capital formation and this would drive technical progress. Therefore, technical progress depends on human capital, and the production of human capital in turn requires public factors such as basic education and basic scientific research. It is assumed that the public goods are financed through a linear income tax rate: the lower the level of public goods and tax rate, the higher is the price of human capital and less human capital is supplied. If the rate of technical progress depends upon human capital, then technological progress is dependent upon taxation and public goods. The contribution by Shell (1967) involves public investment and assumes a public, non-rivalrous stock of technology; a flat-rate income tax is raised to finance the change in the stock of knowledge. Tax has two effects: it increases growth, but also decreases the returns from investment and negatively affects private capital formation.[40]

Ziesemer (1990, 1991, 1995) formulates Schultz's (1964) ideas that public factors – basic education and basic scientific research – are held as necessary for the formation of human capital and the development process. Ziesemer (1990) argues for an essential role of public factors, which are provided by the government and in turn financed by a simple flat rate income tax to introduce an outstanding role of economic policy in economic development. Ziesemer (1991) assumes that, in a growth model with endogenous technical progress, if an externality arises at the firm's level, government intervention is needed to obtain the optimum and perfectly competitive market structure. Hence, a tax subsidy system is introduced to influence the rate of technical progress and brings it to the optimal level of growth. Ziesemer's (1995) model indicates that public factors are used in the formation of

[40] See Ziesemer (1987: 107, 108, 112, 115) and Haslinger and Ziesemer (1996: 230, 232). Ziesemer (1987) summarises T. W. Schultz's (1964) view and indicates that the latter uses Nelson (1959) idea that both basic education and basic scientific research should be viewed as a public good.

human capital and human capital, in turn, is necessary for the production of technical progress. If public factors are financed by a flat-rate income tax, then a higher rate of taxation or shares of public expenditure on education in the GDP will lead to a higher level of public factors, a higher rate of technical progress and will also lead to a higher growth if steady states are stable. In Ziesemer's (1991) model the optimal policy is a technology stock subsidy to reward firms and to provide an incentive for the spillovers of technology formation to the human capital schooling process. In Ziesemer's (1990, 1995) models the optimal policy is a tax financed by government spending on the provision or creation of public knowledge (basic education and basic scientific research). The share of GDP raised and spent on the provision of public factors has an impact on the level of GDP per capita or its growth rate respectively.[41]

One assumption in Romer's (1990) model of endogenous technological change is that technological change arises in response to market incentives, and the latter play an essential role in the model. Romer (1990) assumes that in a growth model with spillover effects, the social optimum can be achieved by subsidizing the accumulation of technology. A subsidy to R&D works to compensate R&D firms for the learning-by-doing and the positive external effects they spillover to other R&D firms; in the absence of R&D, a subsidy creates further incentives for firms to gain entry. Although all the research is embodied in capital goods, a subsidy to physical capital accumulation may be a very poor substitute for direct subsidies that increase the incentives to undertake research. In the absence of feasible policies that can remove the divergence between the social and private returns to research, a second-best policy for a government would be to subsidize the accumulation of human capital. A subsidy to employment in research sector that is financed through lump-sum taxes has the same effects on growth as an increase in the productivity parameter: in the long run, a subsidy will cause an increase in the growth rate (Romer 1990: S72, S74, S93, S98, S99).

Barro and Sala-i-Martin (1992) allow for the effects of fiscal policy on long-term growth and discuss the role of tax policy in various models of endogenous economic growth. In their view, in growth models with learning-by-doing and spillover effects, the social optimum can be attained by financing government consumption purchases with an income tax, and monopoly pricing of new types of capital goods. The tax policies that encourage investment can raise the growth rate and thereby increase the utility of the representative household. In growth models that incorporate public services, the optimal tax policy depends on the characteristics of services. If the public services are publicly provided private goods, which are rival and excludable, or publicly provided public goods, which are non-rival and excludable, then lump-sum taxation is superior to income taxation (Barro and Sala-i-Martin 1992: 645, 660).

In many models of endogenous growth (e.g. Romer 1987, 1990; Grossman and Helpman 1991), technological progress corresponds to an expansion in the number

[41] See Ziesemer (1990: 268–280), (1991: 47–68), (1995: 1–19).

of types of capital goods, inventions require active R&D, and firms are compensated through the retention of monopoly power over the use of their inventions. Therefore, the models involve elements of imperfect competition as the excess of the monopoly price over the competitive one implies that the private rate of return on investment falls short of the social return, and, hence, that the steady-state growth rate is below the socially optimal rate. A common feature in all three types of models – learning-by-doing with spillovers, taxation of income from capital (in models where government services are not subject to congestion) and varieties of capital goods under imperfect competition – is the shortfall of the private rate of return on investment from the social one. This implies that the Pareto optimum can be attained in each model if the government raises the private rate of return on investment to the social one without introducing other distortions. This outcome can be achieved either by subsidizing the purchase of capital goods or by subsidizing the income on capital. Another measure is to subsidize research to raise the private rate of return to the social rate and to provide further incentive to private producers to create new types of capital goods.[42]

Barro and Sala-i-Martin (1995) combine the Arrow (1962) and Romer (1986) assumptions of learning-by-doing and knowledge spillovers. In their model, the social optimum can be attained in a decentralized economy by providing various forms of subsidies that work to raise the private rate of return to investment and thereby tend to eliminate the excess of social over private returns. For instance, the government could induce the private sector to attain the social optimum if it provided subsidies to the purchases of capital goods (an investment-tax credit), financing it through a lump-sum tax. Further options open to the government are: providing subsidies to the purchase of intermediate goods, incentive to expand over time using a lump-sum tax to finance a subsidy, subsidies to final output so that producers receive units of revenue for each unit of good produced, or a direct subsidy to R&D spending to raise the private rate of return on R&D and provide a sufficient incentive for research. Therefore, two policy instruments are needed: one that encourages production of the monopolized intermediates and another that stimulates R&D.[43]

Aghion and Howitt (1998) argue for a role for public intervention to support innovative activities either through the design and use of subsidies (direct targeted or untargeted subsidies) or the design of property rights and patent legislation. They suggest that the R&D investments should be subsidized whenever positive external effects dominate and as a result growth under laissez-faire is suboptimal, but that R&D investment should be taxed if too much "business-stealing" or creative destruction takes place under laissez-faire. They distinguish between targeted and untargeted subsidies; the choice between them depends essentially on availability of information to the government. Targeted R&D subsidies are direct government subsidies that are deliberately aimed at particular sectors (e.g. defence), industries

[42] See Barro and Sala-i-Martin (1992: 651, 652, 654, 655).

[43] See Barro and Sala-i-Martin (1995: 146, 147, 150, 151, 222, 223, 226, 229, 230).

or firms. It may take the forms of public investments in state owned laboratories, research grants, participation in R&D funds, subsidies to enterprises (e.g., input subsidies), credit guarantees, and public investment in high-technology industries. Untargeted subsidies is another important instrument of direct policy intervention in the R&D sector, offered on a non-discriminatory basis according to market decision, without targeting particular firms, industries or projects; untargeted subsidies take the form of research tax credits, tax deductions, credit guarantees, subsidized insurance for risky capital investments, etc. Aghion and Howitt (1998) indicate other forms of government intervention to increase incentives/ subsidies for R&D efforts: through the government's buying up or reducing of the outside investors' share or equity in independent research units and turning it over to R&D firms. Finally, they show that the government has a vital role in enforcing property rights by allowing firms involved to earn monopoly rents as a reward for innovation.[44]

Jones (1998) indicates that many models in the endogenous growth literature have the implication that changes in government policies, such as subsidies to research or taxes on investment, have level effects but no long-run growth effects. For instance, a government subsidy that increases the share of labour in research will typically increase the growth rate of the economy, but only temporarily, as the economy transits to a higher level of income.[45]

Several studies emphasize a role for government intervention and the positive impact of public provision of education and training. For instance, Azariadis and Drazen (1990) suggest a role for government intervention in the education sector (through education subsidies) to avoid low-development traps and thereby promote high sustained growth. Otani and Villanueva (1990), and Barro and Sala-i-Martin (1995) illustrate, for a cross section of countries, a positive impact of government interventions on growth rates coming from the expenditure side (i.e. the share of public expenditure on education of the GDP). Barro and Sala-i-Martin (1995) find that public spending on education has a significant positive effect on growth: a 1.5 % increase of the ratio of public education spending to GDP during the period 1965–1975 would have raised the average growth during the same period by 0.3 % per year. Aghion and Howitt (1998) indicate that centralized funding of education will always favor human capital accumulation and therefore growth in the long run, even though local funding may sometimes be growth-enhancing in the short run.[46] Trostel (2002) suggests that public provision of education through subsidy has the potential to be the most efficient educational policy because it provides incentives and stimulates investment in and accumulation of human capital. A recent report by the UNESCO–UIS/OECD (2003) stresses the role of public finance in enhancing

[44] See Aghion and Howitt (1998: 474, 489).

[45] See Jones (1998: 147, 112).

[46] Otani and Villanueva (1990) is cited in Haslinger and Ziesemer (1996: 236). Azariadis and Drazen (1990) and Barro and Sala-i-Martin (1995) respectively are cited in Aghion and Howitt (1998: 333, 328). See also Aghion and Howitt (1998: 338).

investments and returns from education in a number of selected countries. Chatterji (1995) presents a growth model based on Lucas' (1988) model to explore a potential role for government intervention by subsidizing training to compensate private sector for the positive externalities they generate and to provide more incentives for more investment in the accumulation of skills. The model assumes two possible sources of growth: exogenous technical progress and endogenously produced skills growth. The optimal subsidy on training rises with the rise/strength of the externality generated by the average skill level in output production; it also depends on macroeconomic variables such as the extent of productivity growth from other sources in the economy.[47]

One interesting observation by Aghion and Howitt (1998) indicates that the finding with respect to the complementarity between educational attainment and R&D activities has in turn many interesting policy implications. First, it suggests that "macroeconomic policies which affect rates of innovation and investment will affect the relative demand for workers classified by education, and hence the aggregate skill distribution of employment and earning. (Bartel and Lichtenberg 1987)". In other words, governments will increase the average level of education not only directly through education policy, but also indirectly by actively supporting R&D activities. Conversely, government subsidies to education will increase the profitability of research and development activities, and thereby speed up technological progress (Aghion and Howitt 1998: 339–340).

Few studies examine the practical relevance of the models of growth enhancing policies, particularly for the developing countries. For instance, Haslinger and Ziesemer (1996) indicate that most of the models of publicly financed investment in human capital are basically intended for industrialized and not for developing countries. In their view, in the developing countries, raising the publicly financed investment is hampered by the lack of a well-developed institutional setup to use the instruments of taxation, mainly because of substantial engagement in non-monetised activities, a large informal sector, extreme poverty and different effects from the prevalent regressive trade tax (Haslinger and Ziesemer 1996: 240, 241).[48]

Apart from these practical limitations for the developing countries, in the recent years there is a growing body of literature on the role of public policies and government intervention to promote human capital and technological capabilities in the developing countries. For instance, Lall (1999) discusses strategies to develop skills and capabilities in developing countries and argues that there is a valid case for policies to coordinate, guide and subsidize learning; and to develop such factors as skills and technology where externalities and information failures are particularly pervasive. He identifies two broad successful strategies in the developing world to

[47] See Chatterji (1995: 274–282).

[48] In the case of the Sudan, the extent of the 'non-monetised' activities is less clear. However, like most other typically developing countries, in the Sudan both the prevalence of the informal sector and extreme poverty (cf. UNDP 2010)- and the recent structural reform of fiscal and monetary policies and labour market (cf. UNDP 2006) may imply a promising role for government intervention.

promote skills and learning for competitiveness. First, autonomous strategies to accelerate and guide learning by domestic firms by promoting infant industries, coordinating investments in related activities, overcoming externalities, directing credit, and developing specific skills and institutions. Second, foreign direct investment (FDI) dependent strategies that rely on Transnational Corporations (TNCs) to lead export growth and upgrading, which has two subsets of strategies: those based on targeting TNCs and using industrial policy to guide them in more technology intensive activities; and more passive strategies that rely on market forces to attract and upgrade activities. Korea and Taiwan are leading example of national-led strategy, Singapore and Malaysia of the FDI-led targeted strategy, and Mexico and Thailand of the FDI-led market-led strategy (Lall 1999: 9, 10).

3.6 Conclusions

In this chapter we provide a background for the empirical analysis in the following chapters by surveying the theoretical and empirical literature that emphasize the positive growth effects of human capital and technological progress in increasing and sustaining economic growth. We explain that economic growth theories recognized and provided different perceptions and analytical frameworks for modelling the various effects of technical change, innovation and human capital on economic growth. The major differences arise because the exogenous growth theories perceive and model technical progress and human capital as exogenous variables in growth accounting model, whereas the endogenous growth theory envisages and models technical progress and human capital as endogenous variables determining the rates and differences of economic growth across countries. The endogenous growth theory contributes to improve understanding of the interaction between technological change, human capital and economic growth and fills the gap in earlier growth theories by considering the important endogenous effects of human capital, technological progress and innovation. The endogenous growth theory predicts that in the long run economic growth at the aggregate level is determined by endogenous sources of technological change, human capital, learning by doing, spillovers of knowledge and external effects of human capital. The presence of increasing returns to scale and externalities prevent diminishing returns to accumulation of capital, and so ensure the long run steady state of growth within a dynamic general equilibrium framework. We illustrate that the inclusion of human capital and technological change in growth accounting models motivate endogenous growth literature to provide several interesting explanations of the relationship between human capital and technical change. In particular, it stimulates considerable debate about the complementary relationship between human capital and technical progress, skilled biased technical change, the role of technical progress in skill upgrading and the role of skill and improvement in the accumulation of human capital in skill upgrading. These explanations imply that next to the important endogenous effects of technical progress and human capital for economic growth, the complementary relationships between them and between them and skill upgrading are also important for enhancing economic growth. Finally, we show the advantages and limitations of several measures of technological change and human capital that have been used in theoretical and empirical literature; some of these measures are relevant for the empirical analysis in the next chapters according to availability of data.

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