European Commission

JRC TECHNICAL REPORTS

Macroeconomic Modelling of Public Expenditures on Research and Development in Information and Communication Technologies

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2013

Report EUR 26025 EN

Joint Research Centre

European Commission
Joint Research Centre
Institute for Prospective Technological Studies

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This publication is a Technical Report by the Joint Research Centre of the European Commission.

JRC82943

EUR 26025 EN

This document replaces «Macroeconomic Modelling of Public Expenditures on Research and Development in Information and Communication Technologies» with ISBN number 978-92-79-26275-3 and PUBSY request number JRC 74131. The corrections made in the new document refer to the list of references which has been updated.

ISBN 978-92-79-31143-7 (pdf)

ISSN 1831-9424 (online)

doi:10.2788/37185

Luxembourg: Publications Office of the European Union, 2013

Printed in Spain

PREFACE

Since the 1990s, information and communication technology (ICT) has been an essential driver of economic growth. Between 1995 and 2010, the ICT sectors have accounted for over 20% of EU15 growth, even though they only constitute 5% of EU15 GDP. This *small but mighty* aspect of the ICT sector becomes even more striking if we take the new Member States' economic characteristics into account. The high growth resulting from the ever-increasing pace of ICT-related innovation requires high levels of R&D to be sustained. Indeed, the European ICT sector accounts for over a quarter[1] of overall business expenditure on R&D, which makes it the largest R&D investing sector.

The recently adopted Digital Agenda for Europe[2] (DAE) reemphasises the importance of ICT and the underlying R&D for boosting European performance and competiveness. The DAE, part of the Europe 2020 objectives, identifies areas where ICT can contribute to European development and sets relevant targets. The target with respect to ICT R&D is to double public expenditure on ICT research in ways which leverage an equivalent increase in private spending on ICT R&D.

R&D growth has slowed down or even declined in the vast majority of OECD countries since 2008, with few exceptions.[3] At the EU policy level, it has been recognised that the competitiveness of European firms and industries would be strengthened by substantial innovations from public R&D. It is therefore crucial to ensure that public policies create the right conditions for sustaining and even increasing the support for R&D.[4] Fiscal constraints in advanced economies have limited the availability of (public) resources for R&D, making the choice of investment strategies even more important.

Examining trends in the financing of R&D in monetary value terms may not produce a comprehensive picture. While the Barcelona Council emphasized an increased spending target for R&D, enhancing the across-the-board efficiency of R&D in Europe could also be an important issue. An efficient allocation of R&D resources requires not only an understanding of how R&D expenditure turns into invention and innovation, but also how the created products and technologies impact on the economy and society. Increased R&D investment in the ICT sector may have considerable impact on economic performance, as it goes hand-in-hand with a very high rate of technological progress, output and productivity growth. At the same time, evaluating the impact of policy measures to boost private R&D is neither easy nor straightforward, and it has to be acknowledged that capturing such effects remains difficult due to a range of conceptual and methodological challenges.

In line with this reasoning, one should carefully consider the complexity of public-private investment initiatives as a compound interaction, where policies influence management behaviour in R&D investments and innovation opportunities. There is no

[1] PREDICT 2009: http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=2259

[2] See: Europe 2020 (http://ec.europa.eu/europe2020/index_en.htm), as well as Digital Agenda for Europe (COM(2010) 245) at http://ec.europa.eu/information_society/digital-agenda/index_en.htm, or Innovation Union (SEC(2010) 1161) at http://ec.europa.eu/research/innovation-union/pdf/innovation-union-communication_en.pdf

[3] As for the end of Q3 2011.

[4] Such objectives are debated in COM(2009) 116 available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0116:FIN:EN:PDF

‘one size fits all’ solution but rather a need for a deeper understanding of the relation between public initiatives and private investing activities and a practical framework for adapting policy proposals. Moreover, the effects of policy mix and inherited situations rather than individual or isolated policy initiatives need to be considered.

The aim of this report is to provide an overview of subjects and topics relevant for constructing a coherent framework for macroeconomic analysis of the impact of public spending on ICT R&D, and to set specific modelling requirements for such a framework. The resulting framework needs to incorporate all the linkages between public intervention, the impact on the ICT-producing sector (inclusive on the level of the sector's own R&D), and the diffusion of technology to other ICT-using sectors and consumers.

This report has three parts. The first chapter reviews literature related to public intervention in private R&D, the R&D process, and the diffusion of ICT and its economic impact. The second chapter sets out the characteristics of a macroeconomic model for ICT R&D analysis; the characteristics being based on the three domains discussed in the first chapter. The third chapter proposes a specific initial solution to be implemented within an existing CGE model to account for economics of ICT R&D.

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1. THEORETICAL REVIEW

This chapter introduces the theoretical background related to the impact of R&D on the economy, paying special attention to R&D within the ICT sector. The sequential multistage causal process which links R&D policy intervention with the resulting economy-wide effects covers numerous issues, which must be considered in order to establish a reliable and robust modelling framework. This sequential process begins with categorisation of public instruments relevant to R&D and analysing their impact on the level and performance of private R&D. Once the level and characteristics of the R&D expenditure are established, it is utilised within the innovation process and turned into new knowledge and innovation. The nature and structure of the innovation process has evolved significantly over the past 50 years, and there are number of factors which determine the existence, extent and efficiency of this process. The ICT innovation process is different to all other innovation processes in the sense that its outcome, an ICT innovation, diffuses and makes an impact on an entire, or almost entire, economy. This widespread impact of a single technology is characteristic of General Purpose Technologies. ICT innovation, embedded in newer technology or capital, propagates within an economy subject to cost-benefit analysis in a cyclical process, where the time profile of the ICT diffusion process becomes key to determining the realization of the benefits from technological change. The most important implications resulting from adoption of new technology are in areas of productivity and employment, where ICT has large potential to enhance technological change which, however, is frequently of a skills-bias type, with specific skills being made redundant.

To facilitate presentation of the chapter, the sequential process described above is separated into three consecutive areas: (i) relationship between public and private R&D expenditure, (ii) innovation / R&D process, and (iii) diffusion and impact of ICT.

1.1 Public – private expenditures on ICT R&D

This section looks at the initial stage of the R&D process, where public intervention (e.g. expenditure on ICT R&D) impacts upon private ICT R&D activities. Of interest here are various public instruments which can be used to stimulate private R&D activities, as well as specific magnitudes of private response that such instruments can induce. The private response depends on individual programme designs, sectoral conditions, past, current and anticipated R&D activities of the private companies and the perceived needs of government mission agencies. A presented analytical model helps to analyse cases of substitutability and complementarity from a firm perspective, along with related impact of public instruments. Empirical examples of public intervention through R&D, ICT R&D, and public procurement conclude the section. Although this text does not aim at filling the theoretical gap on economics of public-private R&D expenditures, it does present relevant concepts, which help in understanding of the main mechanisms and classifications of public R&D instruments, as well as the private firms' perception of R&D interventions.

There is no consistent theoretical framework to analyse the relationship between public and private R&D expenditures

It is difficult to disagree with David and Hall who refer to the modelling of public-private R&D funding as a "*heart of darkness*", and to the R&D itself as a "*black box*".[5] Indeed, the relationship between public and private R&D is the most unknown area of realm of economic analysis of technology. The problems in analysing interactions between public and private R&D do not come from lack of research in this area, but rather, as the authors of 'Heart of darkness...' claim, from the lack of a consistent theoretical framework which would help to make sense of empirical findings produced by a number of *measurement-without-theory* types of studies.

This lack of a universal theoretical framework, in turn, can stem from the fact that public interventions into R&D activities undertaken at firm level target different objectives with different instruments, therefore they cannot be assessed against one common desired effect. In contrast, for example, aggregated public expenditure on R&D is frequently assessed for its complementarity or substitutability with private R&D expenditure, with the assumption that the 'desired' relationship is complementarity rather than substitutability. Complementarity, however, may not always be the best outcome of the policy intervention, as will be illustrated later in this section by the case of the Sematech consortium. Here public R&D support allowed consortium companies to eliminate their duplicate R&D effort and led to decrease in private R&D spending. This example shows that a partial substitution of private by public R&D was one of the success factors for the overall programme.

Is complementarity better than substitutability?

Although discussion on the nature of the relationship between public and private R&D expenditures has been long, intense and inconclusive, it seems that there is no evidence of whether one type of relationship (say, complementarity) is better than the other (substitutability). Furthermore, this research question appears not to have been asked, with the exception of David and Hall (2000) who postulated that the 'crowding out' effect may be undesirable if, as a result of public spending, private expenditure on R&D is pushed below a certain minimum level. However, so long as private expenditure remains above this minimum, 'crowding out' may not necessarily be a bad outcome.

The initial message is that no general case can be made with regard to the type of elasticity between private and public R&D expenditure, either factual or desired. The private response depends on individual programme design, sectoral conditions, the past, current and anticipated R&D activities of the private companies and the perceived needs of government mission agencies.

Relevant public instruments can be classified into direct and indirect measures

Governments can stimulate R&D investment by means of a wide range of policy instruments. Cincera et al (2009) classify the most used instruments into direct and indirect measures. The direct ones are comprised of three groups: grants, subsidies and loans, public procurement, and funding of research performed at universities and other public institutions. Among the indirect instruments, the most widely used is the R&D tax credit. The main difference between direct and indirect measures is that indirect support does not affect the choice of research projects undertaken by firms, whereas direct measures (e.g. a subsidy) are distributed for specific research projects and hence promote research in selected areas.

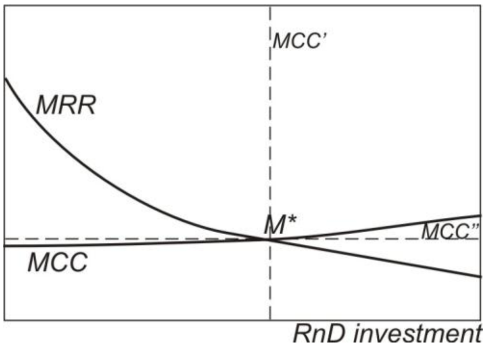
[5] David and Hall (2000).

The research output generated by public establishments such as, for example, universities or public research institutes has an effect on R&D activities in the private sector. Therefore, the efficiency[6] of public R&D is a measure based on the relation between public R&D spending and the resulting additional R&D induced in the private sector. The observed differences in efficiencies across countries can be in part explained in relation to control variables that capture framework conditions (nature of competition, quality of business environment, IP conditions, access to financing, etc).

An analytical model by McFetrige

A framework to analyse the impact of public R&D on the choice of R&D projects in the private sector was proposed by Howe and McFetridge (1976). It assumes that firms chose their R&D portfolio starting with projects with the highest perceived rate of return relative to the R&D investment required, as depicted in the figure below:

Figure 1



$$MRR = f(M^*, X)$$
$$MCC = g(M^*, Z) \qquad (1.1)$$

$$M^* = h(X, Z) \qquad (1.2)$$

Marginal Rate of Return (*MRR*) is the return obtained on R&D projects, whereas Marginal Cost of Capital (*MCC*) is the cost of those projects. Profit maximization implies that a firm keeps investing in R&D up to the point M^* where the rate of return and the marginal cost of funds are equal, as in equation (1.2). The 'shift' variables X and Z reflect other influences important for the portfolio choice. Such influences can include (David *et al.*, 2000):

Factors impacting upon the projects' rates of return:

- The ease of innovation generation, i.e. existence of technological opportunities relevant to the firm's market.
- Degree of demand for the commercialized product or service embedding the innovation.
- Institutional and other framework conditions affecting the appropriability of innovation benefits.

Factors impacting upon the projects' cost of capital:

- Policies that affect the private cost of the projects, such as tax benefits for R&D projects, subsidies, grants or matching programmes.
- Macroeconomic conditions and expectations affecting the internal cost of funds (MCC is valued as the opportunity cost of capital).

[6] *Efficiency* refers to the optimal use of resources in production; can be measured as output-oriented efficiency (producing maximum output from given set of inputs) or input-oriented efficiency (producing given output with minimum inputs).

- Conditions affecting the external cost of funds (above certain investment level a firm would need to look for external funding which makes the MCC curve slope upwards).
- Availability and conditions of venture capital.

Public R&D funding affects firms' decisions by imposing a shift on the *MRR* schedule, *MCC* schedule, or both. A public subsidy for private research infrastructure, for example, would allow the released part of the private capital to be invested in additional R&D projects funded with 'in-house' money, which will be represented by a shift of the *MCC* line (and, consequently, the equilibrium point $M*$) to the right.

The public R&D funding aims at stimulating additional private R&D projects rather than replacing private R&D funding for projects which a firm would have undertaken even without the public assistance. David *et al.* (2000) considers feasibility of such complementarity under three analytical cases with respect to the *MCC* schedule. The first assumes perfectly inelastic cost of capital schedule (vertical MCC' on Figure 1). A public subsidy shifts the MCC' to the right increasing the firm's R&D expenditure by exactly the amount of subsidy. In the second scenario, the MCC is upward sloping, hence its shift to the right imposed by a subsidy increases the firm's R&D performance by less than the amount of the subsidy. In the third scenario, the MCC'' schedule is horizontal, i.e. perfectly elastic. In this case, the schedule shifts downwards because it signals to the equity holders the decrease in the cost of funds internal to the firm. Only under the last scenario would public funding induce additional private R&D spending, i.e. public-private expenditure complementarity would be created.

There are further macroeconomic constraints which may impact on firms' decisions

Another important consideration relates to the constraints imposed by the macroeconomic environment within which firms operate. If a government targets a specific type of R&D and/or an industry or group of firms, this is likely to result in upward pressure on prices of R&D inputs. For example, a significant increase in R&D spending on ICT research will trigger greater demand for personnel with related skills, which will result, assuming inelastic supply, in higher labour costs for firms, a lowering of the MRR schedule and a reduced level of business R&D.

Empirical evidence on ICT R&D public interventions is mixed

Empirical evidence of whether public spending on R&D complements private expenditure and creates 'additionality', or whether it acts as a substitute and 'crowds out' private R&D investment is mixed and by no means conclusive. David *et al.* (2000), in their comprehensive review of econometric evidence of a relationship between public and private R&D funding, report that out of 15 firm-level studies seven reported complementarity, another seven reported substitutability, and one concluded insignificant findings. At the industry and aggregate levels, our reading suggests that 10 studies have found significant complementarity while two have reported insignificant results.

With respect to the efficiency of public R&D expenditure undertaken in ICT industries, the evidence is scarce. One example of such evidence is an econometric assessment of the effects of government subsidies on the semiconductor industry, carried out when Sematech was formed (Irwin and Klenow, 1996). Sematech was an R&D consortium of 14 US semiconductor firms and the US government, formed in response to declining share of the world market held by US semiconductors. The government contributed $100 million annually in matching R&D funds to Sematech over the 1987-1997 period. Sematech's goals were: (i) to encourage firms to do more high-spillover R&D, and (ii) to enhance the effectiveness of the consortium members' R&D spending by eliminating duplicate R&D. The assessment yielded significant evidence in favour of the elimination of overlapping R&D effort. The firms acquired knowledge at reduced cost by sharing the results of the joint R&D effort, which was manifested by an overall reduction in R&D spending of 9%.

An impact of public procurement on living standards via an aggregated, flow-on productivity effect as a direct policy instrument was investigated by Cooper (2007, 2008). Cooper examines the hypothesis that the outsourcing of innovative IT by the public sector leads, through innovation and productivity flow-on effects along the value chain, to improvement in living standards. The flow-on effects are of different magnitudes for different countries, depending on their existing ICT infrastructures. The 'conservative' variant of Cooper's model estimates forgone opportunities for countries, whose public sector does not contract out innovative IT solutions, to range from 400 to 800% returns, relative to the UK as a the leader.

Analysing the relationship between public and private R&D expenditures is difficult because the lack of a broad theoretical framework makes it hard to reconcile empirical findings and produce general conclusions. The analytical model, however, allows us to examine under what conditions public spending can induce additional private R&D expenditures, although such additionality may not initially be the desired result. Empirical evidence is mixed, with more studies reporting complementarity between public and private R&D expenditures.

This section analysed one of the determinants of private R&D activities: public R&D intervention with specific attention to ICT. The next section will look more closely into the innovation process which utilises R&D expenditure as one of the inputs and creates innovation as the output.

1.2 The R&D / innovation process

This section looks more carefully into the structure of innovation process, and distinguishes inputs into the R&D process (e.g. expenditure) from outputs. The output of the innovation process is a special form of intangible capital – knowledge capital, which in many respects is different from traditional tangible capital. The nature and structure of the innovation process has evolved significantly over the past 50 years, and market structure and firm size are important determinants of this process. The section ends with two examples of how the R&D process can be formalised into an economic model: first a micro perspective is illustrated by an example of a multi-stage CDM framework, and second an example of a macro-economic framework is given.

Although R&D and innovation have been long recognized as key drivers of economic growth,[7] understanding of mechanisms which make a firm to invest into the R&D and knowledge creation, which results in rising of the level of R&D in private sector, remains a challenge for both researchers and policymakers.

[7] Technology and technical change were the subjects of scientific enquiry long before the economic concept of productivity was formally formulated in the 1950's (see, for example, Mokyr (1990) for a historical overview).

Knowledge: from 'manna from heaven' to endogenously modelled capital

Contemporary theory about the role that research efforts play in economic development builds on seminal insights provided by Kenneth Arrow, Robert Solow and Paul Romer. Kenneth Arrow (1962) pointed to knowledge created through 'learning by doing' in a form of accumulative experience as an important source of economic growth. Robert Solow (1956) was the first to formally include technical change in an economic model, although he did not attempt to explain its sources – it was assumed to be exogenous. And, finally, Paul Romer (1990) proposed a holistic framework in which knowledge is a specific sort of capital created from investment in the R&D process and subsequently utilized together with other inputs to production activities.

Characteristics of knowledge: durable, non-rival and non-excludable

Knowledge as an input into production possesses a number of distinctive characteristics. Thus, unlike tangible capital, it is not used up within the production process, but continues to contribute to the overall pool of knowledge. Another important difference between tangible capital and knowledge capital refers to the degree of their rivalry and excludability. Rivalry is a technological attribute of a good, referring to the feasibility of its simultaneous use by a number of people or firms – a good is rival if its use by one person precludes its use by another person. Excludability is a technological and legal attribute, and determines to what extent the owner of a good can prevent others from using it – an excludable good can be protected by its owner from use by others. Theoretically, knowledge in the form of a blueprint or a design is non-rival and non-excludable, i.e. it can be used by many firms at the same time. In practice, however, only knowledge as a public good (e.g. basic research) has these characteristics, whereas profit-maximising firms usually attempt to protect designs that they have created or acquired. Private firms protect knowledge by means of no disclosure or property rights, and hence a degree of rivalry and excludability is imposed on knowledge as a good and as a production factor. Some knowledge cannot be separated from its carrier, i.e. it is a tacit knowledge, which is held by a particular researcher (human capital). Tacit knowledge is rival to some extent, since one researcher cannot work for different firms at the same time.

It is important to note here that knowledge can be created in different ways, formal R&D activities being only one of the potential sources of new knowledge. Also, R&D forms only a part of broader intangible capital. A recent study (Riley and Robinson, 2011) analysed the creation of intangible capital, distinguishing between three different types of intangibles: ICT, R&D and OC (organisational capital). It found that in most EU countries, R&D capital constitutes only about half of the intangible capital value which, in turn, is about 40% of new value added.

Large firms can finance R&D from monopolistic rents

Finally, market structure and the size of a firm also impact on the innovation process. Schumpeter pointed out that investment in innovation, which is risky with uncertain outcomes, is usually financed from the monopolistic rents of large firms. A side effect of perfect competition settings which eliminate any monopolistic rents may be to effectively discourage investment in innovation. IP rights ensure some rents for monopolistic innovators and foster innovation.

1.2.1 Structures of innovation process

R&D expenditure is only one of inputs into the innovation process

Although R&D expenditure or investment is only one of the inputs into the innovation process and does not provide any insight into the process itself or the output generated, it attracts a lot of attention because it is relatively simple to measure and the statistics are available. Furthermore, for an economy to benefit from an R&D

output, the new products or services must be marketed, distributed and delivered - activities which can be part of the contemporary R&D management process itself. The structure and complexity of the innovation process constantly evolves.

The innovation model has evolved significantly since the 1950s

Rothwell (1992) provides an overview of the structures of five innovation models. The first and simplest innovation model is that of *technology push.* This was the predominant model in the 1950s and 1960s, providing a supply-side linear approach to the innovation process, in which market information was incorporated very late in the process. Hence market adoption of new products was often problematic. Subsequently, increased competition led to a shift of attention to the market needs. The next model, dominant in the 1970s, namely *market pull*, integrated the R&D process more closely into a firm's operations. The market was perceived as the source of new ideas and firms were seen as responding to market needs by executing a variety of short-term (R&D) projects. From the mid 1970s, recognition of the fact that innovation results from a combination of *push* and *pull* factors rather than exclusively from one of them, led to a *'coupling of R&D and marketing'* model. This model remains a sequential one with, however, numerous feedback loops. The innovation process model which followed from the 1980's well into the 1990's was the *integrated business process*. Along with the accelerating digital revolution and the first ICT consumer products came a shortening of the product life cycle: 'time to market' became a new competition ground. The innovation process was broken into number of parallel or concurrently executed activities, and greater integration with other processes. Finally, from the 1990's, and to a large extent due to the availability of ICT technologies, business processes were integrated through enterprise resource planning and information systems to form a *networked and integrated system.* The time-cost trade off is an important part of firms' competitiveness which, in turn, leads to the formation of strategic partnerships and even deeper integration of R&D into value chains which go beyond enterprise borders and reach upstream to suppliers and downstream to customers.

1.2.2 Modelling examples

R&D expenditure is an inter-temporal investment for a firm

For a firm, the R&D process aims to make its production process more efficient which translates to lower output prices and/or at producing new or improved goods which are valued by customers and lead to market expansion; the two possible effects are process and product innovations respectively. So for a firm, the R&D expenditure is an inter-temporal investment decision.

Invention is to turn money into ideas, and innovation is to turn ideas into money.

The R&D process itself is not straightforward. A firm must first decide whether to undertake any formal R&D at all. In so far as all firms perform some sort of R&D activities related to their business, having established R&D-dedicated expenditure is the result of a formal decision. *Invention* is the desired outcome of the activities related to R&D expenditure. Because invention relies heavily on cognitive human creativity it is necessarily burdened with a degree of uncertainty. The final stage of the R&D process is turning *invention* into *innovation*. Innovation is an invention which has been put into a practical application and which is potentially marketable.[8]

[8] A crude way to summarise this stage is: *invention* is to turn money into ideas, and *innovation* is to turn ideas into money.

Two examples of a generic empirical approach to modelling an R&D process are presented below: one at the micro- level and one at the macro-level.

CDM framework is a popular, multi-stage model to analyse R&D process at a firm level

Micro-level. A popular analytical framework which resembles this sequential R&D process at the micro-level was developed by Crepon *et al.* (1998) (CDM hereafter). This framework has given rise to many subsequent applications and extensions. Although the CDM approach frequently encompasses measures of the impact of innovation on productivity, the overview below focuses on the two initial steps of the innovation process: the decision on the level of R&D expenditure (none is a feasible option), and the innovation production function.

The first stage of the CDM model reflects firms' decisions on whether to engage in R&D processes

The first stage of analysis reflects a firm's decision on whether to engage in research-related activities and, if so, what share of its resources to devote to these processes. To correct for the bias which can occur due to the data being censored,[9] this part of the model builds on a Heckman correction (Heckman, 1979) or Tobit (Tobin, 1958) type 2 (Amemiya, 1984) model. The R&D decision is modelled by the equation (1.3) below:

$$IEI_i = \begin{Bmatrix} 1 \; if \; IEI_i^* = x_{0i}b_0 + e_{0i} > \bar{k} \\ 0 \; if \; IEI_i^* = x_{0i}b_0 + e_{0i} \leq \bar{k} \end{Bmatrix} \tag{1.3}$$

Where IEI_i takes value of 1 if firm i reports positive R&D expenditure; IEI_i^* is unobservable indicator variable such that firm i decides to perform R&D if it is above constant threshold $\bar{k}$; x_{0i} is a vector of explanatory variables, and e_0 is an error term.

Conditional on firm i performing and/or reporting R&D, the equation (1.4) below determines the amount of resources devoted to R&D (research intensity):

$$IE_i = \begin{Bmatrix} IE_i^* = x_{1i}b_1 + e_{1i} \; if \; IEI_i = 1 \\ 0 \qquad\qquad\qquad if \; IEI_i = 0 \end{Bmatrix} \tag{1.4}$$

Where $IEI_i^* = IEI_i$ is the actual research intensity for firm i if this firm does research (ie if $IEI_i^* > \bar{k}$ and $IEI_i = 1$); x_1 is the vector of explanatory variables, and e_1 is the error term.[10]

The second stage of the CDM framework employs an 'innovation production function'

The next step of the analysis will look at how a firm turns its innovation effort into new knowledge by employing a (innovation) production function to describe the process which uses the innovation effort as an input and yields new knowledge. The inputs used are *predicted* values of IE_i^* for two reasons:

(i) some of the firms perform innovation activities but do not report any formal R&D expenditure. Equations (1.3) and (1.4), however, allow us to identify the characteristics of firms which are likely to undertake any innovation effort and then predict their research intensity, and

[9] We observe only firms' reported R&D expenditure. There is, however, consensus that firms which do not report any formal R&D expenditure can perform R&D activities which have an impact on their performance, hence the need for an approach allowing for estimation of R&D effort even for firms which report no formal R&D expenditure.

[10] Necessary assumptions about correlation between e_0 and e_1

(ii) the data most likely to be used with this model is any of the Community Innovation Surveys/Statistics. These datasets are usually confidentialised and some of the variables are presented as intervals rather than actual values. Estimating the actual research intensity provides richer, more variable input for further analysis.

$$INV_i = IE_i^* \alpha + z_i \beta + \varepsilon_i \tag{1.5}$$

Where INV_i is knowledge proxied by the innovation indicators; z_i is set of firm characteristics, and ε_i is an error term.

The model outlined above gives great insight into decisions about performing R&D, its intensity and efficiency which accounts for the diversity of firms' individual characteristics. The specification, however, assumes a recursive structure with no feedback effects and no account for broader, macroeconomic constraints such as limited factors of production or demand (in the short term). An analysis which does not take into account these limitations would provide limited support for policy/scenario analysis and would be unable to determine, for example, how new policy affects employment or prices at country level. A way to account for these drawbacks is to use the micro-study analysis in conjunction with a macro-economic framework, such as Computable General Equilibrium.

A model which underpins most of the relevant analysis today was derived by Griliches from Cobb-Douglas production function

Macro-level. The first model to account for R&D was developed by Griliches. It has been chosen for discussion here because it still underpins most of the relevant analysis today. It derives from a production function of the form:

$$Y = AK^{\alpha} L^{\beta} \tag{1.6}$$

Where Y is a measure of output of aggregation of productive activities, being it a firm, industry, country or union; K represents the use of physical capital, and L is a measure of labour utilised. A is a scaling factor representing productivity. If productivity can be explained by some measure of knowledge available to a firm or country, and taking into account other predictable and random forces affecting the output, the equation above (1.6) can be expressed in its log linear form as:

$$\log Y = \gamma(t) + \alpha \log K + \beta \log L + \delta \log R + \mu \tag{1.7}$$

Where γ represents forces that change systematically over time t; R is a measure of knowledge available to the producing unit and μ accounts for random disturbances. The above specification in the growth rates version takes the form:

$$\Delta \log Y = \gamma(t) + \alpha \Delta \log K + \beta \Delta \log L + \delta \Delta \log R + \mu \tag{1.8}$$

Where Δ is a difference in values of respective variables between two time periods. A common modification of (1.8) is approximating the change in knowledge stock $\Delta \log R$ by ratio of net investment in knowledge, IR, to its current stock R, i.e. IR/R. Then $\delta \Delta \log R$ can be written as $\delta(IR/R) = \delta(Y/R)(IR/Y)$ of which the first RHS term can be defined as: $\delta(Y/R) = dY/dR = \varphi$, hence the (1.8) becomes:

$$\Delta \log Y = \gamma(t) + \alpha \Delta \log K + \beta \Delta \log L + \varphi(IR/Y) + \mu \tag{1.9}$$

Estimation of equation (1.7) or (1.9) using historical data allows us to attribute specific values to relevant parameters which reflect importance, or magnitude of influence of change in the factors on growth of output.

Of interest here is the impact of R&D or knowledge stocks, which is represented by δ - elasticity of output with respect to knowledge stock in equation (1.7) and (1.8), or converted into φ in equation (1.9) - gross rate of return to investment in IR.

In the above specification, R represents intangible inputs utilised in the production process. What the intangible inputs should cover, however, and how those should be statistically measured is problematic. Frequently, as the input used here is accumulated research effort, which is constructed as accumulated past expenditure on R&D as defined by the Frascati Manual (OECD, 2002).

Perpetual inventory method helps to construct time series data on stocks of R&D

To overcome a lack of long time-series data on respective R&D expenditures, the perpetual inventory method suggested by Griliches (1979) to evaluate stock of R&D is usually employed. The stock in the first year for which data is available, RDS_0, is calculated as:

$$RDS_0 = \frac{RD_0}{\rho + \lambda} \tag{1.10}$$

Where ρ is average growth of RD expenditure over the period for which data is available, λ is a depreciation rate, and RD_0 is a figure for expenditure in an initial year. Stocks for further periods are calculated as:

$$RDS_t = RDS_t(1-\lambda) + RD_{t-1} \tag{1.11}$$

R&D expenditure is a measure of input, however it is frequently used to proxy output of the R&D process

Such calculated stocks of past research efforts, RDS, are frequently used as measures of knowledge or innovation used by a producing entity as presented in equations (1.7)-(1.9), i.e. it is assumed that $R = RDS$. These two, however, conceptually represent different measures where one (*RD*) is an input into the research process measured in currency-expenditure, and the other (R) is the output of this process (the output being much more difficult to capture, quantify and measure). Hence, the output of the research process is a function, $\tau(\cdot)$, of the inputs:

$$R = \tau(RDS, Q) \tag{1.12}$$

Intangible resources used by firms reach beyond R&D

It is becoming widely recognised, that the measures of intangibles used by firms cover not only narrowly defined R&D activities, but also other inputs Q. For example:

"The finding that other factors are also important for business innovation does not render R&D irrelevant. It simply means that innovation policy has to look at more than one explanatory factor and that these additional factors are of great importance".[11]

[11] (Australian Government Productivity Commission, 2007, pp 36)

"Intangible investment in general, and not only R&D investment, drives productivity growth. [...] Our knowledge of the contributions of intangibles to economic performance remains incomplete."[12]

The latter study revealed the significant importance of three different types of intangible capital: organisational capital, ICT capital and R&D capital. The study found that in most of the EU countries, R&D capital constitutes only about half of the intangible capital value which, in turn, is about 40% of new value added.

This section analysed how R&D expenditure is being transformed into new knowledge and innovation taking into account the evolving structure of the innovation process, market structure and firm size. It is important to reemphasise the fact that formal R&D activities are only one of the potential sources of new knowledge, where R&D forms only about a half of overall intangible capital in the EU. The presented micro- and macro- frameworks formalised relationships between various factors that decisively affect the outcome of the R&D process.

The next section will show how the outcome of R&D activity –ICT innovation – diffuses to other sectors and affects their performance.

1.3 Diffusion and impact of ICT

The ICT innovation process is different to all other innovation processes in the sense that its outcome, an ICT innovation, diffuses to and makes an impact on an entire economy. This specificity made many think of ICT and ICT-enabled innovations as investment goods of a special kind: a general purpose technology. This section reviews the mechanisms of technology diffusion. ICT innovation embedded in newer technology or capital propagates in a cyclical process subject to cost-benefit analysis, with the time profile of ICT diffusion becoming a key to the realization of the benefits from technological change. We present the most important implications resulting from adoption of new technology in areas of productivity and employment, where ICT has large potential to enhance technological change. The section concludes with a review of empirical and theoretical approaches which aim to capture the impact of ICT on economy.

1.3.1 Diffusion of ICT

ICT is categorised as a network GPT which has fuelled technological progress since the 1990s

The pervasive diffusion of ICT as a general purpose technology has enabled the latest wave of technological progress since the mid-1990s. This process has been accompanied by the high growth of investment in ICT and related services on the one hand, and the growing scope for the application of ICT on the other. The swift drop in the relative prices of ICT hardware has enabled the ICT sector to produce key ICT technologies and has fuelled strong competitive pressure in their production. The OECD (2003a) estimated that the prices of key ICT fell during the 1990s by between 15% and 30% annually, making investment in ICT attractive to firms.

The level and the rate of the ICT diffusion differs considerably between countries

Gradually, ICT became omnipresent in virtually all stages of manufacturing and in the majority of service-provision mechanisms. Being a network technology, ICT diffusion became a self-enabling process where the more firms and consumers use the network, the more benefits it generates. The extent to which different ICT

[12] http://www.innodrive.org/attachments/File/Innodrive_Manual_2011_Piekkola(ed).pdf

technologies have diffused across economies has, to a large extent, determined the economic impact of ICT on output and productivity. ICT investment has accelerated in most OECD countries over the past decade, though the level and the rate of ICT diffusion differs considerably between countries. This has occurred mainly because some countries have started to invest earlier and have invested more in ICT than others. Investment in ICT not only enhances an individual firm's productivity by means of productive equipment and software, but also develops the infrastructure for the use of ICT and creates a range of network externalities.

Time profile of the ICT diffusion process is a key determinant for realization of benefits from technological change

Economists have long been aware of the fact that technological advances spread slowly and that the relationship between the beginning of economic exploitation of a general purpose technology and the effects on aggregate productivity growth, as well as the pattern of diffusion, is non-linear. Under these conditions, the time profile of the ICT diffusion process becomes a key in determining the realization of the benefits from technological change. Economic theory provides some insights into the relation between the new general purpose technology diffusion and productivity.

Technological innovations are not evenly distributed over countries, industries and time

One of the fundamental insights provided by Schumpeter (1939) in this regard is that technological innovations are not evenly distributed over countries, industries and time. The importance of diffusion phenomena within the context of economics and technical change has been recognized in a number of subsequent studies, for example by Mason, Clark and Dunlop who pointed out in 1941 the need for studies to investigate how rapidly "an innovation spreads from enterprise to enterprise". Initially, the subjects of studies on diffusion of technology were specific capital goods or innovations. Mansfield (1961) investigated the diffusion of twelve innovations that were, in his view, of outstanding importance. He looked at the *'rate of imitation'* i.e. how rapidly firms in four industries came to use these 12 innovations, and found that the probability that a firm will introduce a new technique is proportional to the number of firms which are already using it and to the profitability of that adaptation, and inversely proportional to the size of the investment required.

Diffusion of ICT is a subject of cost-benefit and supply-demand analyses

The diffusion of ICT is a dynamic process which interactively involves forces of supply and demand, and is subject to cost-benefit analysis from both suppliers and consumers of digital technology. Applying a general cost-benefit analysis notion, a firm may adopt new (ICT) technology if a net present value of the adoption, $NV(t)$, is positive:

$$NV(t) = V(t) - P(t) > 0, \tag{1.13}$$

where $V(t)$ is the value that the technology has for a firm. It is calculated as the discounted sum of the annual profit gains (present value) resulting from its adoption:

$$V(t) = \int_{\lambda=t}^{\infty} \Pi(\lambda,t)\exp(-r\lambda)d\lambda, \tag{1.14}$$

where $\Pi(\lambda,t)$ is the expected annual profit gain in time λ resulting from adoption of technology in time t with $t < \lambda$, and r is the discount rate, and $P(t)$ is cost of acquiring the technology that the firm must bear in order to use it. To account for possible obsolesce of technology[13] the specification (1.14) needs to be augmented

[13] This is important for the ICT where technological progress is particularly rapid.

with respect to the discount rate r, which than would need to reflect possibility of technological obsolescence occurring in any time period (Ireland and Stoneman, 1986).

GPT (e.g. ICT) is adopted in two cyclical phases: accumulation and growth

Helpman and Trajtenberg (1994, 1996) studied the process of the technology adoption on the macro-level and incorporate the notion of general purpose technology into a growth model to explore the economy-wide dynamics that it may generate. They found that each time the new general purpose technology appears, it generates a cycle consisting of two distinct phases: the first is the accumulation of resources, investments and development of complementary inputs and the second is a period during which growth, with rising output, real wages and profits, occurs.

Factors that affect the diffusion of ICT can be broadly grouped in two categories: cost and business environment

The issues of cyclicality of adoption of new technology and unpredictability and a time lag of the innovation-related outcomes were further studied by Greenwood and Jovanovic (1999). They combine slow diffusion and learning-by-doing in a putty-putty vintage model in which new plants are the carriers of the new technology. In this model, entry involves the additional cost of building a new plant, which leads to a temporary productivity slow-down. Another potential source of productivity slowdown, aside from the loss of resources due to the establishment of new plants, is the loss of efficiency due to technology adoption. Slow recovery is accompanied by a steep learning curve, slow aggregate replacement of old vintages, and *second* mover advantages that prompt firms to delay entry. This latter observation is in line with the studies of Silverberg *et al.*, (1988), and Jovanovic and Lach, (1989). Several factors that affect the diffusion of ICT can be broadly grouped in two categories: cost factors and business environment factors.

Europe showed higher prices on ICT investment goods compared to the US and Canada throughout the 1990s

Cost factors of the ICT diffusion. Since investment in ICT is of high importance with regards to profitability, a firm's decision to adopt ICT technologies depends on the balance of associated economic, time, and administrative costs and benefits. As highly technological assets, ICT investment goods are traded internationally. It could therefore be expected that ICT prices would be equal across countries. However, as shown by the OECD (2001, 2003a), this is not the case. ICT investment goods in Europe, for example, had considerably higher prices than in the US and Canada throughout the 1990s. The high cost of ICT investment is usually associated with barriers to trade (such as non-tariff barriers related to standards, import licensing and government procurement), and lack of competition. Another factor is the availability and cost of services associated with operation and maintenance of the hardware, and with communication. One example of such services is the cost of the leased lines, which are the building blocks of business-to-business electronic commerce. The Internet, a communication platform for ICT riding on network access technologies such as fixed line, mobile cellular, wireless terrestrial and satellite, is recognised as a knowledge infrastructure, which to a great extent determines the effectiveness of ICT goods and services. The cost of the Internet in particular and of telecommunication in general is one of the important considerations when deciding on ICT investment. Regulatory reform to increase competition in the telecommunication industry is one of the main factors that drives down these costs.

Firms' decision to invest into ICT depends on product market regulation and innovation climate

Business environment factors of ICT diffusion. A Firm's decision to invest in ICT depends on whether the existing business environment is "ICT-friendly". This factor has several layers. First, the level of ICT investment in a country is related to product market regulation. Product market regulation can hamper or encourage competition, which affects both the prices and the quality of ICT goods and services. In turn, ICT can also influence the competitive climate in the product market and stimulate the introduction of new forms of regulation. Thus, for example, ICT may generate new ways of consuming and distributing goods and services, which were unknown before, and thus enable firms to enter new markets (electronic sales, electronic goods). Second, the innovation climate is another important determinant of the business environment. Innovations play a crucial role in the successful implementation of ICT. This factor is related to ICT as a GPT, which has great potential for technological improvements and a broad scope for innovation-related complementarities. For example, the use of ICT enables firms to restructure their organizations through adoption of a less complicated administrative hierarchy, faster information processing, and outsourcing. It also allows them to engage in new markets and new activities through e-commerce, and to develop and personalise their production by inventing software packages and providing consultancy services.[14] And finally, labour market regulation may influence ICT investment decisions. Since innovation through ICT investment is a risky activity, in highly regulated labour markets firms may be constrained in adjusting their labour resources and organization structures to accommodate innovative changes and make ICT work effectively.[15]

Diffusion of ICT involves a lot of trial and error, learning-by-doing and self-reinforcing co-ordination failures.[16] Stoneman (2002) lists several factors which may affect the returns on new technology and, hence, impact on the adoption decision:

- Location – some geographical locations may be preferred over others.
- Previous investments in technology may have various impacts – if the new technology is only a marginally improved vintage of the old one, a firm may find that the new investment is not cost efficient; if the new technology is complementary to the previous one, ownership of the previous technology may be a factor contributing to the new investment decision. Also, an experience from using the previous technology (learning by doing) may be of some importance.
- Other inputs – skilled labour or in-house R&D can be important or even necessary factors when adopting a new technology
- Expectations – what a firm expects to gain from an investment into a new technology (equation (1.14) above) is, to a certain extent, a subjective valuation based on belief and varies across firms.

Access to finance – the new investment can be financed either internally or through loans, the latter can imply different interest rates for different firms. The cost of borrowing of money for investment will affect the discount rate and the final potential benefit from an investment (1.13).

1.3.2 Impact of ICT on productivity and employment

The discussion so far has hinted at notable changes in the sources of productivity growth over the last few decades. These changes are related to the ICT-producing industry, at least in the developed countries. Additionally, the penetration of ICT in the

[14] See Wiel et al. (2004) for discussion.

[15] See Gust and Marquez (2002) and Bartelsman et al. (2002) for a theoretical discussion and empirical evidence of this issue.

[16] Helpman et al.(1994) , Bayoumi et al.(1999) David (1990), Greenwood and Jovanovic (1999), Bassanini et al. (2000), Gourlay and Pentecost (2002).

production process of other, ICT-using sectors, is boosting their output and also generating new (ICT) innovations. Therefore ICT, as the result of a continuous innovation process and as a tool for further innovation in the production processes of other sectors, has attracted the attention of theoretical and empirical researchers, and policy-makers for some time.

ICT and productivity

There are three main ways in which ICT impacts on the economy

ICT influences the production process in different ways: it creates a demand for new types of physical capital and skills, new products and new production stages, new ways of management, marketing and delivery, and a new producing and consuming environment. Most studies identify three modes in which ICT has an impact on the economy:

- Production of goods and services by the ICT sector. One way to grasp the economic importance of ICT is to consider the role of its producers in the economy-wide value added or GDP. This approach focuses on the production process of ICT goods and services and on the extent to which ICT-induced technological progress increases multi-factor productivity (MFP) in the ICT-producing sector.
- Usage of ICT goods as capital input in ICT-using industries. ICT as a capital good contributes to higher labour productivity through overall capital deepening. This approach considers ICT capital deepening to be a result of the increasing demand for ICT products and services as inputs to ICT-using services.
- ICT as a special capital input. This approach considers the spillover effects generated by ICT, which exceed direct returns on ICT capital. Appropriation of ICT by other sectors increases overall productive efficiencies (and raises MFP) through various channels such as production gains, lower transaction costs, business and employment creation through spill-over of innovation and knowledge, and a greater connectivity and flexibility of markets.

Microeconomic studies emphasize the complexity of the link from technology to productivity

The two most widely-studied means by which ICT has an economic impact, namely ICT capital deepening and TFP growth in ICT-producing sectors, measure the direct growth contribution of the use and the production of ICT. At the same time, microeconomic studies emphasize the complexity of the link from technology to productivity. ICT is a network technology, which implies that the more people and firms use the network, the more benefits it generates. The use of ICT throughout the economy may also have a contagious effect, helping firms to increase their overall efficiency, thus raising TFP growth. Likewise, ICT use may contribute to network effects, such as lower transaction costs and more rapid innovation, which should also improve TFP. To leverage ICT investment successfully, firms must typically make large complementary investments and innovate in areas such as business organisation, workplace practices, human capital and intangible capital

Structural issues are important determinants of the economic impact associated with ICT

The rise of MFP growth due to ICT is a reflection of technological progress in the production of semi-conductors and related products and services in the ICT sector. The *size of the ICT sector* is thus an important determinant of the economic impacts associated with ICT. Having an ICT-producing sector can be important, since ICT-production has been characterised by rapid technological progress and has been faced with very strong demand. The sector has grown very fast, and made a large contribution to economic growth, employment and exports. Having a strong ICT sector may help firms that wish to use ICT, since the close proximity of producing firms could have advantages when developing ICT applications for specific purposes. It should also help generate the skills and competencies needed to benefit from ICT use. Moreover, it could lead to spin-offs, as in the case of Silicon Valley or in other high technology clusters. To shed light on the direct contribution of the ICT industry to overall growth in the 1990s, Bassanini et al. (2000), for example, consider the share of total labour productivity growth of two industries in the ICT sector (the *Office and computing machinery* industry, ISIC 3825, and the *Radio, TV & communication equipment* industry, ISIC 3823). Their results confirm that this industry enjoyed an annual average labour productivity growth above 10%, which is almost 5 times higher than in the manufacturing industry, and accounts for about 40% of total manufacturing labour productivity growth. These results can be replicated internationally, though to the lesser extent than in the US. Having an ICT sector can thus support growth, although some empirical work has shown that it is not a prerequisite.

Before 1992 firms used ICT to substitute away from labour and capital, while more recently a shift towards a complementarity relationship between ICT and capital has been identified

Affordable ICT-enabled solutions fuel the demand for ICT products and services and create additional incentives for ICT firms to innovate. Consequently, a better and a cheaper ICT sector output results in wider benefits for both firms investing in ICT and consumers buying ICT goods and services. However, the relatively lower cost of ICT is only part of the picture: ICT is also a technology that offers large potential benefits to firms by enhancing information flows and productivity, and to society by shaping production, consumption and the institutional environment. The pervasiveness of ICT progress has altered the very nature of ICT as a production input. Chwelos et al. (2010) posited that before 1992, firms used ICT to substitute away from labour and capital, while more recently firms have begun to use ICT in very different ways. Instead of ICT capital deepening, new capital-based applications now require ICT for their functioning, resulting in a shift towards a complementarity relationship between ICT and capital. The overall pattern of empirical results supports this thesis, while also raising new questions about the nature of ICT as a production factor.

We have so far established that the impacts of the ICT sector are examined in several ways in the economic literature: directly, through its contribution to output, employment or productivity growth, or indirectly, for example as a source of technological change affecting other parts of the economy. However, there are several issues related to the economic impacts of the ICT sector that would benefit from further analysis. For example, questions can be raised regarding the link between having an ICT sector and benefiting from ICT investment and use. Some analysts have used the experience of a country such as Australia to suggest that having a large ICT manufacturing sector may not always be necessary. This hypothesis would benefit from more research as there could be spill-over effects associated with having an ICT manufacturing sector. Moreover, in order to benefit from ICT use, it may be important to have a well-developed domestic industry providing software and computer services to firms using the technology.

ICT and employment

ICT changes the nature of employment, unemployment and job search

A wide range of theoretical and empirical studies address the interaction between ICT and employment from different angles: ICT as a factor that changes the dynamic of employment and wages, ICT as a skills-biased technology that determines the dynamics of the labour markets in terms of employment and wages, and ICT as a factor that changes the nature of employment, unemployment and job search.

Employment impacts of ICT can be direct, through growth of the ICT sector and ICT-using industries, and indirect through multiplier effects.

ICT impacts employment directly and via multiplier effects

A good example of the multi-channel effect of ICT on employment is illustrated in a study by Katz (2009). It shows that broadband penetration can increase employment in at least three ways. The first is the direct effect of jobs created in order to develop the broadband infrastructure. The second is the indirect effects of employment creation in businesses that sell goods or services to businesses involved in creating broadband infrastructure and the third is induced effects in other areas of the economy. The last two ways can be expressed, through an input-output model, as multiplier effects. The relationship between broadband diffusion and employment through these mechanisms is a causal one, although the estimate of employment growth relies on a number of assumptions.

The right skills and competencies must be in place for ICT to be developed and used effectively

The dynamic character of the ICT-producing sector (and of other high technology industries) is transmitted into the rapid employment expansion of new firms in these industries. New entrants in these sectors –if they survive – grow much more rapidly than firms in other parts of the economy. Matching the skills of workers to the new technology also requires considerable investment. For ICT to be developed and used effectively, the right skills and competencies must be in place. Policies which aim to enhance basic literacy in ICT, build high-level ICT skills, encourage lifelong learning in ICT, and enhance the managerial and networking skills needed for the effective use of ICT, are particularly relevant. Moreover, a certain degree of labour mobility is needed to seize the new opportunities associated with ICT, which may require changes to regulations in some countries.

ICT is a skilled-biased technology which induces the demand for skilled workers and reduces the demand for unskilled ones

The majority of economic studies confirm the complementarity between technology and skills in improving productivity performance and posit that ICT investments need to be accompanied by a co-investment in human capital. A wide range of empirical investigations find that *ICT is a skills-biased technology,*[17] which induces the demand for skilled workers and reduces the demand for unskilled ones. This relationship proved to be persistent when tested on both micro[18] and aggregate[19] data. Observed shifts in labour demand towards skilled labour are believed to be caused by the impact of informational technologies which, by definition, are biased towards more highly-educated workers. Increased specialization and growing employment in skills-intensive industries and jobs occurs within rather than between industries and results in the growing divergence of labour markets both in terms of employment and wages. The skills-biased technical change theory has prompted an overwhelming number of empirical studies to suggest that the use of new ICT technologies in the workplace is fuelling an increase in demand for skilled people, particularly tertiary graduates, and a relative decrease in demand for unskilled workers (Machin and Reenen, 1998; Toner, 2010). In broad terms, the main message is that skilled people complement new technologies, while unskilled labour can be substituted by automated processes. This thesis is used to explain why, in the face of strong expansion in tertiary education,

[17] Machin et al (1996), Haskel and Slaughter (2002), Bound and Johnson (1995), Berman et al. (1998), Autor et al. (1998).

[18] A few examples are: Green et al. (2001)(2001) for France, Haskel and Heden (1999) for the UK, Caroli and Van Reenen (1999) for France and the UK, Baldwin et al. (1995) and Sabourin (2001) for Canada.

[19] Machin (1996), Machin and Van Reenen (1998), Autor et al. (2003)(2003) and Autor et al. (2006) are among the most cited ones.

returns to college have remained positive and thus do not suggest an over-supply of highly educated graduates (OECD, 2008).

ICT improves performance of labour markets

The impact of ICT as a general purpose technology on employment can be also seen in providing advanced and flexible platforms that match employees and job-seekers, i.e. in developing the alternative means for the labour demand and labour supply to meet. In particular, a relatively new phenomenon on the labour market is online recruitment. This could be seen as a combination of using ICT and ICT skills in the process of offering and finding employment. Job search and recruitment through the internet have been the attribute of the most successful dot-com companies. Online job search has advantages compared to conventional ways, due to its very low cost and speedy means of transmitting information. Advantages for jobseekers include the possibility of reaching a very large pool of jobs free of charge and using convenient tools to personalize and organise the job-search process. Advantages for the firms seeking to recruit include cost-saving, anonymised pre-screening services, the ability to edit job advertisements, and post them to multiple locations, track reactions, etc.

Online recruitment costs a firm around one-fifth of what it would cost using print media

Freeman (2002) reports that recruitment over the internet costs a firm an estimated one-fifth of what it would cost using print media. This type of ICT impact on employment highlights the importance of network economies and economies of scale, and allows speedier clearing of the labour market, reduced transaction costs, better matching between jobseekers and employers, which altogether leads to a more efficient economy. However, one should not be too optimistic about this type of ICT effect on employment: empirical evidence should be studied carefully. For instance, Kuhn and Skuterund (2004) found some empirical evidence that internet job searches are ineffective in reducing unemployment duration, or that internet job searchers are negatively selected on unobservable characteristics.

1.3.3 Theoretical and empirical approaches to seize the impact of ICT

ICT capital investments have to be deflated with quality adjusted price index to account for their improvements not reflected by declining price of capital

From the economic theory point of view, the paradigm for ICT-based economic growth relies on shift in ICT-using industries' investment patterns towards capital goods that embed new ICT technology. The new capital goods can be differentiated either across types or across vintages with the vintages of ICT capital improving over time. The improvement in this context reflects two aspects: improvement in quality and reduction in price. For example, the decline in acquisition prices for computers allows us to account for the number of computers acquired through an investment. In parallel to the price decline, however, the computers are becoming faster, are fitted with more memory and equipped with new features. To reflect this quality improvement, the investment value needs to be deflated with a quality-adjusted price index to, in effect, calculate the capital services provided after such investment (Schreyer, 2000).

The quality of ICT capital was estimated to have improved at over 10% annually in the 1992-2002 decade in the OECD countries (Bassanini and Scarpetta, 2002). The British Office for National Statistics published a quality adjusted producer price index for computers and other data processing which fell from 385.5 in 1992 to 100 in 2000, and 47.5 in 2004. However, if official price indices do not fully reflect such quality changes and if new equipment which embodies technology is more productive (on the margin) than older equipment, the investment should be accompanied by an increase in measured TFP growth. TFP will grow faster than average for as long as the rates of investment are heightened.

The heterogeneity of ICT capital is not well reflected by assumptions of standard neoclassical growth models

This heterogeneity of quality of capital is not properly considered in the standard features of neoclassical growth models which assume that uniform, perfectly substitutable, homogenous capital is used in the production process. This implies that all capital has identical productive capacity (marginal contribution to output) and new investment only adds to the total capital stock. *This view of capital denies de facto any connection between the pace of investment and the rate of technological progress* (Boucekkine et al., 2011). To deal with decreasing marginal rates of return to capital and to account for technological progress, neoclassical theory assumes a disembodied diffusion of technology. The disembodiment approach was, however, questioned by Solow (1960):

"*The striking assumption is that old and new capital equipment participate equally in technical progress. This conflicts with the casual observation that many if not most innovations need to be embodied in new kinds of durable equipment before they can be made effective. Improvements in technology affect output only to the extent that they are carried into practice either by net capital formation or by the replacement of old-fashioned equipment by the latest models*."

New innovations together with the rate of investment determine the rate of technological progress

Hence, in reality, we would expect that newer capital investment embodies more advanced technology when compared with older vintages of capital. It means that new capital is better than old capital and that the new innovations *together* with the rate of investment determine the rate of technological progress. For example, a mainframe IBM computer of the 1970 vintage had the capacity of 12.5 million instructions per second (MIPS), whereas an average personal computer worth a few hundred dollars of the 2005 vintage had the capacity of 500 MIPS.[20] With respect to ICT capital, evidence obtained by Atzeni and Carboni (2006) supports the hypothesis that ICT is different from conventional capital in the rate of technological progress and in the compatibility between old and new capital. Some estimates of the magnitude of technical change embodied in capital goods include:

- 12% annual improvement in productivity of capital over 1972-96 in US (Sakellaris and Wilson, 2001).
- 12% annual improvement in embodied capital in US manufacturing (Hobijn, 2001).
- 3% quality improvement in new vintages of equipment (Gordon, 1990).

New vintage of computers is 31.5% more efficient than the previous year's vintage; for software, the annual efficiency gain is 'only' 11.5%

However, no empirical studies provide explicit estimates for the rate of technical change embedded in ICT capital goods. It could be argued that the implicit rate of depreciation of the ICT capital proxies the rate of embedded technical change. For example, the EU KLEMS project (Timmer *et al.*, 2007) for the construction of capital accounts assumes that capital stock, KS, is a weighted stock of past investments:

$$KS_t = \sum_{\tau=0}^{\infty} \theta_\tau I_{t-\tau} \qquad (1.15)$$

[20] Example from Berg and Lewer (2007).

Where the weights θ_τ represent the efficiency of a capital good of age τ relative to the efficiency of new capital good; $I_{t-\tau}$ is the investment in period $t-\tau$. Assuming some constant rate of age-efficiency loss, such as geometric one, i.e. $\theta_t = (1-\delta)^t$, yields:

$$KS_t = KS_{t-1}(1-\delta) + I_{t-1} \tag{1.16}$$

The equation (1.16) is a standard depreciation-investment identity where δ is the depreciation rate of capital (see, e.g. equation (1.11) in the previous section). Timmer *et al.* (2007) use the following (Table 1) estimates of annual depreciation rate for the ICT related equipment and software:

Table 1: Geometric depreciation rates

Asset type	δ
Computing equipment	0.315
Communications equipment	0.115
Software	0.315

The interpretation of the above estimates is that a new vintage of computers is 31.5% more efficient than the previous year's vintage. For software, the annual efficiency gain is 'only' 11.5%.

There are two types of effect of technological progress on productivity: through embodied components (ICT equipment) and through disembodied components of technological progress

From the early 1990s, ICT as a general purpose technology became the subject of a growing number of empirical studies. Early empirical research on the impact of ICT on productivity was largely inconclusive. One of the main reasons for this ambiguity in research conclusions in the early 1990s can be summarized by the Sollow's paradox: "computers are everywhere except in productivity statistics". On both macro and micro levels, ICT investment is the measure of ICT diffusion that is most closely linked to the economic impacts of the technology. However, it only provides a partial view of the diffusion of ICT.

Over the past few years, statistical offices in OECD countries have developed a wide range of indicators of ICT diffusion, based on internationally harmonised surveys of households and businesses, which have allowed researchers to produce robust empirical estimates of the relation between ICT and productivity. Thus, for example Bassanini et al. (2000) shed light on the relationship between innovation, diffusion of innovation and growth, and examined the relationship between technological progress proxied by the change in multi-factor productivity and R&D (OECD, 2000). Their results suggest two types of effect of technological progress on productivity: through embodied components (ICT equipment) and through disembodied components of technological progress. Their results are largely consistent with most new growth theory.

Overview of the empirical approaches

Bellow we present a short overview of the empirical approaches used to estimate the impact of ICT on economic growth, productivity and employment.

Growth accounting relies on decomposing the economic growth constituent production inputs' contributions

Approaches that use aggregate data.

The growth accounting approach is the most widely used approach to measure the contribution of ICT investment to economic growth at the macro level. It consists of decomposing the growth of value added into the growth of production inputs, namely labour, ICT investments and non-ICT investments. All growth accounting decomposition exercises require some measure of the elasticity of value added to each input. Elasticities are unobservable and researchers have to rely on estimation techniques to capture them. Economic studies have adopted two different approaches: (i) cost share in the value added and (ii) econometric techniques. The two approaches are outlined below.

Cost share in the value added. In this approach, the elasticity of each input is assumed to be equal to its cost share in the value added. This assumption is based on the prediction from economic theory that the remuneration of a given input should be equal to its marginal productivity. This result rests on a set of strong hypotheses about the technology of production (Cobb Douglas, with constant returns to scale), the behaviour of firms (profit maximisation) and the degree of competition (perfect competition) in the markets. Furthermore, this approach assumes that all increase in value added which is not explained by growth in production inputs is due to an increase in total factor productivity (TFP). As a result, all deviation from the above hypotheses and all measurement errors in the statistical data are misinterpreted as differences in TFP across sections and over time.

This approach, however, has been used to produce a number of influential economic studies. Jorgenson and Stiroh (2000) applied the Jorgenson's (1967) *production possibility frontier* and found that in the US after 1995, computer hardware played an increasing role as a source of economic growth and that average labour productivity grew much faster between 1995-1999 due to capital deepening as a direct consequence of the fall in ICT prices and the increase in TFP. Colecchia and Schreyer (2001) extended this approach to nine OECD countries up to the year 2000 and found that in the preceding two decades, ICT contributed between 0.2 and 0.5 percentage points per year to economic growth, depending on the country, while in the mid-1990s, this contribution rose from 0.3 to 0.9 percentage points per year. Using a similar framework to the UK data, Oulton (2002) found that the ICT contribution to GDP growth increased from 13.5% in 1979-89 to 20.7% in 1989-98. According to this study, ICT contributed 55% of capital deepening during the period 1989-98 and 90% in the period 1994-98. Crepon and Heckel (2002) evaluated the contribution of ICTs to the growth of value added via two channels: the accumulation of IT capital across all industries and the TFP gains in the ICT-producing industries. They used the data on ICT investments in French firms and found that, over the period 1987-1998, ICTs accounted for 0.7 percentage points of the yearly value added growth, 0.3 points from capital deepening and 0.4 points from TFP growth in the ICT-producing industries.

Econometric techniques. The second approach relies on estimating the inputs' elasticity through econometric techniques. This approach has two advantages. First, it does not impose any *a priori* hypotheses on the technology of production, the behaviours of firms or the degree of competition in the markets. Second, it permits a direct estimation of the inputs' productivity, in such a way that measurement errors are not incorrectly counted as TFP. The drawback of the econometric approach is that its implementation is difficult and requires a large data set. The literature about the econometric approach is large, and examples of integrated, general models can be found in Morrison (1986), Boskin and Lau (1990) and Nadiri and Prucha (2001). O'Mahony and Vecchi (2005) use a dataset of US and UK non-agricultural market industries to estimate the impact of ICT capital on output growth. As traditional industry panel data analysis fails to find a positive contribution, they employ a dynamic panel data approach in order to account for heterogeneity across industries. Pooled estimates show a positive and significant return of ICT capital on output growth. ICT investment produces excess returns as compared to the prediction from growth accounting. Individual countries' estimates imply a larger impact in the long-run in the US than in the UK. Some macroeconomic studies focus on specific ICT infrastructures such as telecommunication or broadband infrastructure and find positive and significant impacts on growth. Roller and Waverman (2001) investigate the relationship between investment in telecommunication infrastructure and economic performance in 21 OECD countries over the period 1971-1990. Controlling for simultaneity and country-specific fixed effects, they find a causal relationship between telecommunication infrastructure and aggregate output. Their results suggest that a 1 percentage-point increase in telecommunication penetration rate (main telephone lines per capita) increases aggregate output growth by an average 0.045 percentage points. A recent application of the econometric approach to estimate the contribution of three types of ICT investment (computer, software and communication) was undertaken by the OECD (2011). This study is based on the data from 26 industries in 18 OECD countries over the period 1996-2007.

In recent years, longitudinal databases have increasingly incorporated links to data on firm use of ICT

Approaches that use firm-level data.

Over the past decade, analysis of the impact of ICT use has benefited from the establishment of longitudinal databases in statistical offices. These databases allow firms to be tracked over time and may contain information combined from several surveys and data sources. They typically cover large and statistically representative samples of firms, which are important, given the enormous heterogeneity in firm characteristics and performance (Brynjolfsson and Hitt, 1996, 2000; Doms and Bartelsman, 2000; Lichtenberg, 1993). In recent years, longitudinal databases have increasingly incorporated links to data on firms' use of ICT; the linked data can subsequently be explored in analytical studies. Other types of data can be integrated too, which is important since empirical studies suggest that the impact of ICT depends on a range of complementary investments and factors, such as the availability of skills, organisational factors, innovation and competition (OECD, 2003a, 2003b).

Firm-level data provides strong evidence for the impact of ICT use. ICT use may have several implications at this level. For example, the effective use of ICT may help firms gain market share at the cost of less productive firms, which could raise overall productivity. In addition, the use of ICT may help firms expand their product range, customise the services they offer, and respond better to client demands; in short, to innovate. Moreover, ICT may help reduce inefficiency in the use of capital and labour, *e.g.* by reducing inventories. These effects may all lead to higher productivity growth. For a long time, these and related effects have been difficult to capture in empirical studies, which has contributed to the so-called "productivity paradox". However, a growing number of firm-level studies provide evidence on such impacts, suggesting that the productivity paradox has largely been solved due to the availability of the broader, more robust and statistically sounder micro-data. The diffusion of ICT may also have impacts that go beyond individual firms as it may help establish ICT networks, which produce greater benefits as more customers or firms are connected to the network (spillover effects). For example, the spread of ICT may reduce transaction costs, which can lead to a more efficient matching of supply and demand, and enable the growth of new markets that were not feasible before. Increased use of ICT may also lead to greater scope and efficiency in the creation of knowledge, which can lead to an increase in productivity (Bartelsman and Hinloopen, 2005). These spillover effects would drive a wedge between the impacts of ICT that can be observed at the firm level and those at the sectoral or aggregate level. Combining these three levels of information would help to shed light on this issue.[21]

A complex and highly nonlinear set of relationships between the various aspects of ICT R&D represents a major challenge for policy at the regional, national and international levels

Concluding note: The role of ICT in enhancing economic growth and socio-economic development is now well established both in academic research and in policy priorities. Measuring the impact of ICT uptake is a critical input to ICT policy-making. A complex and highly nonlinear set of relationships between the various aspects of ICT R&D represents a major challenge for policy at the regional, national and international levels. ICT-enabled convergence of the industries must be addressed in a systematic way. Because the ICT industries operate within networks, their particular characteristics must be considered. For example, the consumer's optimal strategy may not and usually is not the society's optimal structure. Moreover, network economics become more complex when the boundaries of the various ICT sectors merge or are not well defined. For example, the cable, broadcasting, telecommunications and internet sectors can no longer be viewed in isolation, and many mobile phones are complements or substitutes for wire-line access to internet.

Public investment in the development of ICT as an enabling general purpose technology is necessary to achieve an efficient allocation of research and development resources. In line with this view, the industry data suggest that ICT capital growth is associated with industry TFP accelerations with long lags of between 5 to 15 years. Indeed, controlling for past growth in ICT capital, contemporaneous growth in ICT capital is negatively associated with the recent TFP acceleration across industries. Efficient allocation of resources to ICT R&D could either be assumed to be done by a social planner or by the private sector subsidized by a government that taxes agents in the consumption and application sectors to pay for fundamental research. This approach is broadly consistent with the empirical generalization that the public sector has played an important role in the development of almost every general purpose technology in which the developed economies are globally competitive.

[21] See, for example, OECD (2003a) for the application of the combined micro-macro approach.

2. THE SPECIFICATIONS OF THE MODEL

Building on the theory reviewed and empirical evidence presented in the first section, this chapter sets out more specific requirements for development of a macroeconomic model with capacity to simulate ICT R&D related policies. Because development of a macroeconomic, multi-sectoral and multi-regional model from basic components is not needed for the project (and it is also a time consuming and laborious exercise), what is envisaged is the modification of an existing model. Modification here means enrichment of an existing macro-model with theory and data relevant to issues of ICT R&D.

The research context for this study is formed by combining statistical methods and economic theory related to a role of ICT – related research and development activities in economy, as described in the first chapter.

2.1. The economic context

The boundaries for the economic context relevant for this study can be identified through consideration of a sequential process resembling the flow of economic activates related to ICT R&D. A change in the level of (ICT) R&D expenditure can have *direct* implications (points *a* and *b* below) for the inputs to ICT R&D activities, and *indirect* productivity effects (point *c* below). Indirect effects, in turn, can trigger two mechanisms that lead to productivity increases: firstly, changes in productivity through the ICT sector's contribution to output, employment or productivity growth and, secondly, the ICT sector, as a source of technological change, may affect other parts of the economy.

Three separate, but interlinked, domains of analysis with respect to the economics of ICT R&D are relevant for this study:

1. The aggregate R&D devoted to ICT is made up of private (BERD) and public (GBOARD) contributions. The public component can be an important instrument for stimulating private spending. It is therefore necessary to analyse and take into account issues of substitutability and complementarity between private and public R&D expenditures in order to capture the impact of a change in private R&D expenditure resulting from a change in public R&D commitment.
2. R&D activities require labour and capital inputs and, furthermore, R&D builds on previously developed knowledge, possibly not only domestic but also foreign. The direct economic effects of a change in R&D expenditure are often associated with change in utilisation of the inputs, the employment-related implications of which are essential.

Change in aggregate ICT R&D spending affects the productivity of the ICT sector, and has implications for growth, competitiveness and employment. The R&D effort results, inter alia, in innovations which improve the productivity (*process* innovations in particular) of the ICT sector. The quantitative relationship between the change in ICT R&D expenditure and the resulting change in the productivity of the ICT sector is an important component of the study. Furthermore, the effects on ICT-*using* sectors[22] have implications for growth, competitiveness and employment. Product innovations, due to increased ICT R&D expenditures, result in the production of new, better products, including ICT capital investment goods. These products, when used in other

[22] ICT-using sectors comprise both ICT and non-ICT sectors.

sectors, have the potential to affect the productivity of those sectors. The potential to influence the productivity of ICT-using sectors differs among sectors and would be expected to be, for example, higher in services than in agriculture. The study should account for this impact of increased ICT R&D expenditure on the productivity of other sectors.

2.2 The modelling context

As outlined above, R&D activities in general, and ICT R&D activities in particular, have a potential effect on entire economies. Therefore, quantitative assessment of the role of ICT R&D needs a framework which covers the economy as a whole. Such a framework, at the macroeconomic level, has to include representation of the parts of the economy which are important from the ICT R&D viewpoint, as either being able to affect the rest of economy through R&D activities, or being affected (directly or indirectly) by the output of the R&D process.

The many ways in which ICT R&D interacts with the economy requires a comprehensive modelling approach to assess its impact. Such a modelling framework should integrate all possible channels of interaction between R&D ICT and the economy in a dynamic, multi-sectoral and multi-country framework. The multi-sectoral perspective is needed to reflect the internal structure of an economy which absorbs ICT innovation, while the multi-country framework is required for tracking international diffusion of ICT technology. Inter-temporal dynamics is needed to take account of the ICT innovation production life cycle, the transformative nature of new technology, its temporal diffusion and the changing overall socio-economic environment, within which ICT technology increasingly operates. The above requirements point towards a dynamic multi-country Computable General Equilibrium (CGE) class of models as a suitable framework for the analysis to be undertaken.

2.3 Data description

The database used with the model should reflect ICT R&D activities and account for the inputs used (labour, capita, other) and services/output provided which, in turn, are used further in the economy as input by other sectors. In the cases where an existing database (most likely) which does not account for ICT R&D specifically is modified, it needs to be either supplemented with the relevant data or, if the database is aggregated up to a level at which the ICT R&D is combined with other data, it needs to be disaggregated back to a level with separate ICT R&D representation.

ICT R&D data used should be collected through national surveys according to the guidelines laid down in the *Frascati Family* of guidelines. National R&D surveys are carried out in all EU countries but it should be remembered that they may not cover the whole range of ICT R&D activities. The data is collected using the same methodology (laid down in the Frascati Manual) in most countries and should, as a rule, be internationally comparable. Another possible source of data are the OECD Database (Business Enterprise Intramural Expenditure on R&D (BERD) by Industry and Source of Funds) and the annual series of PREDICT[23] reports focusing solely on R&D activities in the ICT industry.

Pragmatically, it is advisable to begin with a small-scale operational model in order to test the empirical approach and correct at an early stage if necessary. The small-

[23] Consult the following for information: http://is.jrc.ec.europa.eu/pages/ISG/PREDICT.html

scale operation al model, however, should cover a minimum of EU economy, with respect to ICT R&D, to produce verifiable results and avoid analysis based on countries which perform none or very little ICT R&D. Therefore, the regional aggregation for the analysis should, as a minimum, identify separately two major EU Member States and an aggregate region. The two member states must be chosen from the following set: France, Germany, Italy and UK. The aggregate region is the rest of the World. As for the sectoral composition, the database representing the economy should comprise no less than five sectors: the ICT sector and four other sectors. The four other sectors should be chosen as aggregates to best represent the impact of the policy simulated, i.e. the impact of an increase in ICT R&D spending. The factors taken into account for aggregating the four sectors should include the magnitude of the potential impact of increased spending on ICT R&D on different sectors in the economy.

2.4 Model description

The study should be based on an economic model with the capacity to assess the macro-economic implications of the policy, such as CGE or macro-econometric models. The model's framework should encompass the supply and demand sides of the markets (both intermediate and final goods and services), as well as representation of household and government roles. The model should allow for the incorporation of public interventions including aspects related to taxation (e.g. taxes collected and taxes on R&D) and should be able to account for various types of public spending (e.g. R&D). It should incorporate national accounts and the main macroeconomic aggregates. It should also reflect inter-sectoral and inter-national interactions such as goods-specific trade and mobility of capital and labour (with realistic assumptions about degree of mobility for labour and capital).In addition, it should account for the diffusion of ICT R&D output (namely new knowledge, ideas, blueprints, designs, etc.) between the countries, and between the countries and the rest of the world.

Due to the inherently inter-temporal nature of some aspects of the study (e.g. a time interval separating the R&D investment and the resulting productivity adjustment), the study should be based on a dynamic model. The dynamics should be incorporated through endogenous engines of growth consisting of the accumulation of physical capital, knowledge stock/capital (related to ICT R&D at minimum) and human capital.

With respect to the role of ICT R&D in the economy, the model should cover the following areas:

a) ***Change in private ICT R&D investments as a result of an increase in public ICT R&D spending.*** Increased ICT R&D spending will result in the expansion of ICT R&D activities and, in turn, in greater demand for inputs used by the R&D activities. The model should account for change in employment associated with ICT R&D, accounting for the specificity of this labour market. The movement of skilled labour to ICT R&D activities leveraged by the additional R&D spending will also have implications for other sectors which will release the skilled labour, which should be identifiable from the model.

b) ***Change in productivity of the ICT sector resulting from the increase in public and private ICT R&D spending.*** The R&D effort results, inter alia, in innovations which improve the productivity (*process* innovations in particular) of the ICT sector. The model should link changes in ICT R&D expenditure (preferably through accumulable and depreciable R&D capital stocks) and the resulting change in the ICT sector's productivity. The impact of productivity changes on the economy (growth, employment) should be identifiable at the sectoral and national levels.

c) ***Effects on ICT-using sectors.*** Product innovations due to increased ICT R&D expenditures result in the production of new, better products, including ICT capital investment goods. These products when used in other sectors have the potential to impact on the productivity of those sectors. The potential to influence the productivity of ICT-using sectors differs among sectors and would be expected to be, for example, higher in services than in agriculture. The model should account for this impact of increased ICT R&D expenditure on the productivity of other sectors.

d) ***Welfare analysis for EU citizens***. The model should provide insight into welfare inferences at the EU- and country-levels. The welfare should be measured as Equivalent Variation, Compensating Variation or in other accepted form. The welfare measure should be decomposable into its major sources, such as allocative efficiency effect, technology effect, endowment effect and terms of trade effect.

3. SUMMARY AND CONCLUSIONS

This report is a first step towards the construction of a modelling framework for the assessment of ICT R&D-related policies. The need for such a framework arises from the fact that proper management of ICT technologies, including ICT innovation, is a necessary condition for economic growth and prosperity, and governments can play an important role in facilitating innovation. The importance of innovation is recognised, for example, by the fact that the Innovation Union has been placed at the heart of the Europe 2020 strategy, and the Digital Agenda for Europe, which specifically addresses ICT-type of innovation.

The first part of this report reviews literature on the impact of R&D and ICT R&D on the economy. The innovation process is not straightforward, and innovation cannot be manufactured in the same way as material goods. Innovation relies heavily on cognitive human creativity and, therefore, it is necessarily burdened with a degree of uncertainty. Because the innovation process does not always produce successful innovations, levels of R&D differ widely between firms, industries and countries.

To encourage firms to undertake more inventive activities, governments use policy instruments such as subsidies, tax credit or public procurement. Empirical evidence shows that public spending on R&D can induce additional private research expenditure or, to the contrary, reduce private sector spending on specific types of R&D. Although complementarity between public and private research expenditures is frequently perceived as more desirable than substitutability, no generalisation can be made as to whether one type of elasticity is better than another. This is because government programmes have different designs, aims and objectives and the effectiveness of each programme depends on the specific conditions faced by a targeted firm.

Because ICT is a general purpose technology with a wide application scope and even bigger potential for further improvement, ICT innovations have a profound effect on the economy when they are propagated and applied by firms, governments and consumers. The process of diffusion of ICT technology is not instantaneous and depends on many institutional and behavioural factors. The two most relevant effects that ICT technology can induce on the adopting entities are related to productivity and employment.

Due to the inherent uncertainty of the innovation process, no definite assessment of the economic effects of R&D policy can be made. However, an economy-wide quantitative modelling framework could assist assessment by estimating the direction and magnitude of direct, indirect and secondary effects of R&D intervention, more widely and more precisely than any other complementary method.

The second chapter of this report identifies the general requirements for a modelling framework to be used for ICT R&D analysis. Since there are existing models which can be used as a base framework, the guidelines focus on the specific requirements for an R&D module to be developed. This add-on module must be fully integrated with the base model.

Since the model will be used with ICT R&D policy scenarios, it must be able to account for relevant public instruments, such as public spending on ICT R&D, subsidies or tax credit. Firms' investments into ICT R&D will be based on an endogenous inter-temporal optimisation mechanism with the public instruments affecting the investment portfolio.

Change in R&D intensity will be associated with the ICT sector's changing dynamics, the employment-related implications of which are of crucial importance. The specification of the R&D module therefore needs to allow assessment of these implications with respect to the specificity of the labour market and the different labour skills classes. The model also needs to account for the impact of R&D innovation on the performance of the ICT sector (process innovation) and on the performance of the ICT-using sectors (product innovation) via capital-embedded innovation modelled through spillovers. Finally, it should be possible to assess the welfare implications at Member State and EU levels.

Conclusions

The main conclusions drawn from this report fall into the following categories: (i) construction of the model, (ii) the flexibility of modelling specifications for public intervention, (iii) the employment implications for the ICT sector, and (iv) the diffusion of ICT innovation.

Construction of the model

Multi-sectoral, multi-regional CGE models, with or without R&D treatment, are very complex in design and laborious to develop. The theoretical structure of these models consists of thousands of behavioural equations which reflect the main macroeconomic mechanisms at various geographical levels of economy. Furthermore, the equations have to be parameterised and complemented with vast amounts of data in order for one of these models to become operational and computable.

CGE models do not usually account for R&D activities. In those models which do account for technological change, its treatment varies from inclusion of technological shift-variables which allow for an exogenous, one-time shift in efficiency of a factor or productivity of a sector, to more advanced specifications where technology is linked to R&D expenditure and creation of new knowledge.[24] The models with endogenous technology, however, do not distinguish between different types of R&D activities. The separate treatment of ICT R&D is essential due to its particularly widespread diffusion and omnipresence in the economy with potential impact on not only ICT-producing sectors, but also on the ICT-using industries.

Therefore, the development of the CGE model suitable for analysis of ICT R&D-related policies will be accomplished by modification of an existing model rather than development of a new model from a scratch. ICT R&D theory is complementary to the standard CGE structure in the sense that R&D adds further details to the basic CGE structure so that the model better reflects this particular issue. At the same time, this base structure is necessary for the R&D to build upon.

Flexible specification for public R&D intervention

Public expenditure on ICT R&D is the main policy instrument for influencing the level and allocation of private R&D activities. However, as stressed at the beginning of this report, the nature of the impact of public ICT R&D expenditures on private ICT R&D spending is difficult to generalise since it depends on individual programme designs,

[24] See Section "*Examples of existing CGE model with some treatment of technology*" in the Annex for overview.

sectoral conditions, the past, current and anticipated R&D activities of private companies and the perceived needs of government mission agencies. Therefore, in order to maintain the usefulness of the developed model for analyses of various options and scenarios related to different assumptions of the policy, it is important to maintain flexibility in the ways public instruments will affect the model's behaviour. Specifically, it is important to provide an adjustable mechanism which allows us to choose between the types of relationship (substitutability vs complementarity) between public and private R&D expenditures, and also for the specific magnitude of this specification.

Employment implications in the ICT sector

One of the crucial insights to be provided by the model is an assessment of employment dynamics related to increased spending on ICT R&D. R&D activities require labour and capital inputs and, furthermore, R&D builds on previously developed knowledge, possibly not only domestic but also foreign. The direct economic effects of a change in R&D expenditure are often associated with a change in the utilisation of inputs, the employment-related implications of which are essential. The accuracy and quality of this insight hinges on the specification being developed to include R&D inputs in the production structure of the base model. The employment implications should be identifiable at both sectoral and national levels.

Diffusion of innovation

The specifity of ICT technology relates to is its omnipresent impact on all business processes within the economy. The implication for the modelling exercise is that R&D expenditure and any resulting innovation benefits not only the ICT-producing sector (process innovation) but also all the users of the ICT goods produced (product innovation). Since the observed impact of ICT on the economy is without doubt profound and significant, capturing the diffusion of ICT innovation and its economic impact is essential to fully account for the effects of ICT R&D expense.

ANNEX

Definitions

In this report, terms are defined as follows:

a. **Model:** is regarded here as consisting of database, code, and auxiliary files, as described below:

   - The ***database*** contains quantitative information about stocks and flows which describe a part of economy over a period of time. The database developed for this project should be based on existing database and complimented with data relevant to ICT R&D activates to form a comprehensive, harmonized and balanced dataset.
   - The ***code*** consists of equations which form behavioural rules based on economic theory. Those rules reflect (model) behaviour of different agents in economy and allow for simulating policy interventions in order to assess their impact.
   - Auxiliary files include all remaining components needed to use the model such as: parameter files (values needed for parameterisation of the model, can be included in the database), sets files (needed to group information in the database into, for example, sectoral groups or economic regions), and other model-specific files.

ICT sector: The reference definition of the Information and Communication Technologies (ICT) sector and for the related R&D expenditures for the project is based on the operational definition of OECD (Frascati Manual (2002), p.188).[25] The ICT sector consists of the following NACE[26] rev. 1.1/ISIC v. 3.1 industrial activities:[27]

Manufacturing
30 Manufacture of office, accounting and computing machinery
32 Manufacture of radio, television and communication equipment and apparatus
33 Manufacture of medical, precision and optical instruments, watches and clocks
Services
642 Telecommunications Services
72 Computer and related activities

A further discussion about this definition can be found in the "The 2010 report on R&D in ICT in the European Union",[28] Annex 1, pp.129-131.[29]

b. **R&D**: The Frascati Manual defines research as follows: Research and experimental development (R&D) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and

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25 Frascati Manual: See OECD at: http://www.oecdbookshop.org/oecd/display.asp?CID=&LANG=EN&SF1=DI&ST1=5LMQCR2K61JJ

26 NACE: Nomenclature générale des Activités économiques dans les Communautés européennes (NACE) refers to the industrial classification as defined in Revision 1 which is used by Eurostat.

27 In case of using other industrial classification statistics an appropriate correspondence should be applied.

28 See at http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=3239, pp.141-142 (Annex 6).

29 Available at: http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=3239

society, and the use of this stock of knowledge to devise new applications.

The term R&D covers three activities: basic research, applied research and experimental development:

1. Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view.
2. Applied research is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
3. Experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed. R&D covers both formal R&D in R&D units and informal or occasional R&D in other units.

ICT R&D: In the context of this report ICT R&D refers to R&D undertaken in the ICT sector. The ICT R&D expenditure consists of public ICT R&D expenditure (GBAORD) and private ICT R&D expenditure (BERD). For further details see, for example, "The 2010 report on R&D in ICT in the European Union".[30]

GBAORD covers not only government-financed R&D performed in government establishments, but also government-financed R&D in the business enterprise, private non-profit and higher education sectors, as well as abroad (Frascati Manual, § 496).

A further discussion about Sectors of R&D performance and Sectors of Financing of R&D can be found in the PREDICT Report 2010[30], Annex 6, pp.141-142.

NB: The expressions "ICT R&D" or "R&D in ICT" are used as equivalent here.

Examples of existing CGE model with some treatment of technology

A report commissioned by EC DG INFSO[31] provides some overview of selection of CGE models' structure suitability for modelling of ICT as GPT. Although there are no existing models which would encompass both ICT sector and endogenous technological change with representation of relevant R&D-related instruments, there are models which have some parts of the required solution. The following models were considered: Worldscan, Nemesis, Quest, Multimod, IFs, Nigem, OEF, GEM-E3. Out of this group, however, Quest, Nigem, OEF and GEM-E3 do not constitute endogenous treatment of innovation process and/or technological change, hence are not suitable for modelling of the R&D related policies. The following table summarises relevant characteristics of the four remaining CGE models:

[30] http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=3239

[31] *Evaluation Models and Tools for Assessment of Innovation and Sustainable Development at the EU level*, College of Europe, 2006

Table 2: CGE models with endogenous treatment of innovation and technological change processes.

	Worldscan	Nemesis	IFs	Multimod
Technology transmission mechanism	R&D→TFP	R&D→supply R&D→demand	R&D→output	R&D→TFP
Spillovers	Yes	Yes	No	Yes

The most detailed specification of technology transmission appears to be embodied in the **Nemesis** model. The mechanism is structured in three stages:

- *from R&D to knowledge* – the model contains sector-specific knowledge stocks which depend not only on the sector's R&D, but also on other sectors' R&D and government R&D.
- *from knowledge to innovation* – changes in stock of knowledge transmit into process and product innovations which, in turn, translate in to change in TFP and change in product quality respectively; the two types of innovation have different impact on economic performance.
- *from innovation to economic performance* – process innovations (TFP change) impact upon unit price of output and the respective demand (wrt. price elasticity of demand), whereas the product innovations impact on unit efficiency and unit price with subsequent effect on demand.

Although the original **Multimod** model does not endogenise technological change, in its extension in it has TFP set as a function of domestic and foreign R&D stocks.

Similarly to Multimod, **Worldscan** has an extension which endogenises technological change. In the Worldscan it takes a form of another nest in the value added tree-like structure part of the production structure. The additional nest combines R&D specific labour and capital to produce knowledge which, in turn, supplements value added from traditional factors of production to form an augmented value added to be later combined with intermediate inputs. Such specification allows firms to optimise between traditional factors of production and investment into R&D activities.

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European Commission
EUR 26025 – Joint Research Centre – Institute for Prospective Technological Studies

Title: Macroeconomic Modelling of Public Expenditures on Research and Development in Information and Communication Technologies

Authors: Wojciech Szewczyk, Anna Sabadash

Luxembourg: Publications Office of the European Union

2013 – 45 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series –ISSN 1831-9424 (online)

ISBN 978-92-79-31143-7 (pdf)

doi:10.2788/37185

Abstract
Since the 1990s, information and communication technology (ICT) has been an essential driver of economic growth. Between 1995 and 2010, the ICT sectors have accounted for over 20% of EU15 growth, even though they only constitute 5% of EU15 GDP. The high growth resulting from the ever-increasing pace of ICT-related innovation requires high levels of R&D to be sustained. Indeed, the European ICT sector accounts for over a quarter of overall business expenditure on R&D, which makes it the largest R&D investing sector.
A set of EU policy initiatives emphasise the importance of ICT and the underlying R&D for boosting European performance and competiveness. In order to ensure that public policies create the right conditions for sustaining and increasing the support for R&D, an appropriate measuring framework based on the thorough review of the best available methodologies need to be devised. This framework will serve as a tool for choosing investment strategies for public spending that create a favourable climate for an increase of private spending on ICT R&D, and to turn investments into economic growth and employment through innovation.
This report aims to provide an overview of subjects and topics relevant for constructing a coherent framework for macroeconomic analysis of the impact of public spending on ICT R&D, and to set specific modelling requirements for such a framework. The overview is structured to resemble the sequential multi-stage causal process which links R&D policy intervention with the resulting economy-wide effects, and covers the following issues: the relationship between public and private R&D expenditure, innovation and the R&D process, and diffusion and impact of ICT. Furthermore, building on the theory reviewed and empirical evidence presented, the report identifies the general requirements for a modelling framework to be used for ICT R&D analysis. Since there are existing models which can be used as a base framework, the guidelines focus on the specific requirements for the development of an R&D module. This add-in module is called upon to provide specific initial solutions to account for economics of ICT R&D, and needs to be fully integrated with the base CGE model.

LB-NA-26025-EN-N

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ISBN 978-92-79-31143-7