European Commission

Research, innovation and economic growth

Knowledge production function and R&D investment

Research, innovation and economic growth: Knowledge production function and R&D investment

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EXECUTIVE SUMMARY

Innovation, education and adoption of information technologies are at the centre of the European Union economic growth strategy (Europe 2020). The basis of this strategy is primarily motivated by the productivity gap observed between Europe and its competitors which is believed to be due to lower investment in research and innovation and insufficient use of information technology.

Within the European Commission, the responsibility for research and innovation policies primarily lies with the Directorate-General for Research and Innovation (DG RTD), which monitors and analyses national policies and provides recommendations on how member states could improve the quality and quantity of their research. In order to facilitate policy-making, DG RTD uses QUEST III, a macro-economic model developed by the Directorate General for Economic and Financial Affairs (DG ECFIN). However, despite its sophistication, QUEST III is not designed to evaluate a number of innovation policies and reforms.

DG RTD has identified a series of updates or changes required in QUEST III in order for the model to better support research and innovation policy. To this end, this report explores possible modifications that could be introduced into QUEST III, focusing on the Research and Development sector (R&D). In particular, a series of econometric analyses have been carried out in order to quantify the relationship between:

- Innovation, international transmission of knowledge and R&D investment;
- Knowledge creation and the public-private composition of R&D; and
- Private and public R&D investment and the extent to which government expenditure on research and innovation stimulates or crowds out private R&D efforts.

The analysis provides a number of interesting insights:

- **International transmission of knowledge and the level of high-skilled workers within a country are economically and statistically significant drivers of innovation.** The estimated elasticity of R&D typically ranges between 0.5 and 0.7 and is lower than the international spill-over effect which usually ranges between 0.8 and 1. This suggests that the international diffusion of knowledge over the last two or three decades has played a pivotal role in the innovation process;
- **It appears that R&D has been more important for technology followers (non-G7 countries) than technology leaders (G7).** The results for the international spill-overs show the opposite pattern with G7 countries benefiting from international knowledge more than the non-G7 countries. An asymmetric effect is also documented in Bottazzi and Peri (2007) but in the opposite direction with G7 relying more on their own resources and non-G7 being more dependent on international stock of knowledge;
- **There is some indication that private and public R&D have differential impacts on knowledge creation.** It appears that private R&D is more effective in countries that are on the technology frontier (G7) than public R&D, whereas public R&D plays a more significant role in knowledge creation for technology followers (non-G7 countries);
- Governments have an array of micro and macro policies at their disposal to support private R&D investment and consequently innovation. The macro analysis carried out in this report suggests that **public investment in private R&D projects and higher education research stimulates privately-funded R&D.** The evidence related to direct government R&D investment (i.e. research carried out in national labs and institutions) is mixed but typically suggests no significant

effects. Overall, the results suggest that public R&D complements private research efforts.

- **The estimated impact of government-funded R&D on business-funded R&D is quite stable across different models** and indicates that a 1% increase in public-funded business investment leads to c.0.2% increase in business-funded R&D. **Investment in higher education has the largest effect on private R&D relative to the other two public R&D investments** with an elasticity of around 0.5 (although estimates depend on model specification). Furthermore, the impact of university R&D is higher in the non-G7 countries relative to G7.

The report provides a large number of estimates using alternative model specifications and assumptions. These estimates are occasionally sensitive to the modelling strategy adopted. It is recommended that the results are interpreted with care acknowledging the inherent limitations of the analysis including the imperfect proxy of innovation and collinearity of explanatory variables, and the pros and cons of the different modelling strategies (for instance, alternative proxies of R&D employment, estimation methods and samples considered).

1 Introduction

The impact of research and innovation on productivity, employment and long-term economic growth has been extensively studied and documented. For instance, recent evidence suggests that much of the productivity gains in recent years have come from innovation and that countries that invested more in research and development (R&D) before and during the financial crisis of 2008 have been the most resilient during the economic downturn (Conte, 2014; Ciriaci, 2013).

The economic benefits of research and innovation are widely recognised by governments and policy-makers, who increasingly support R&D through fiscal incentives (tax credits and grants), micro policies that aim to improve the quality of research, and investment in human capital (Becker, 2015). Expenditure in higher education research, for example, has increased from $54.3 billion in 1985 (14% of total R&D expenditure) to $134.8 billion in 2011 in G7 countries (18% of total R&D investment).[1]

The first R&D policies implemented in the US and Europe have been inspired by the rise of the Japanese economy which enjoyed high growth rates until the 1990s based on a strong technological base and high commitment to R&D. The growth of the Asian tiger economies over the 1980s and mid-1990s has also been based on a high-tech strategy (Bloom et al., 2002).

The European Commission, in its recent communication on *Research and innovation as sources of renewed growth*[2], highlights the importance of research and innovation investments for economic growth and urges member states to put in place the necessary reforms to increase the quality and relevance of those investments.

1.1 Context

QUEST III is the macroeconomic model the Directorate General for Economic and Financial Affairs (DG ECFIN) uses for macroeconomic policy analysis and research. For instance, Roeger, Varga and Veld (2009) study the impact of various policies that promote knowledge creation in the spirit of the Lisbon Treaty and Varga and Roeger (2014) demonstrate the effect of structural reforms in Southern Europe in the context of the recent crisis.

Despite its sophistication, QUEST III is not designed to take into account a number of R&D aspects as well as potential policies and reforms. The Directorate-General for Research and Innovation (DG RTD) has identified a series of updates or changes required in QUEST III in order for the model to better support research and innovation policy, which are as follows:

- **Task 1.1: Knowledge production function.** Update the parameters of the knowledge production function.
- **Task 1.2: Knowledge diffusion.** Incorporate the impact of scientific and technology diffusion on total productivity and economic growth.
- **Task 1.3: Public and private R&D.** Allow public and private R&D investment to have a differential impact within the knowledge production function.
- **Task 2: Skills accumulation.** Endogenise the process of skill accumulation and incorporate the role of government policies that influence the quantity and quality of human capital.

[1] 2010 US dollars

[2] https://ec.europa.eu/research/innovation-union/pdf/state-of-the-union/2013/research-and-innovation-as-sources-of-renewed-growth-com-2014-339-final.pdf

- **Task 3: Impact assessment.** Better capture the effect of R&D policy and reforms on quality of R&D.

1.2 Objectives

This report focuses on tasks 1.1 and 1.3 and explores how QUEST III could better take into account the dynamics of knowledge creation and R&D investment.

Objective 1: Update the parameters in the knowledge production function

A key aspect of the R&D sector within QUEST III is the knowledge production function which assumes that innovation is generated by high-skilled workers and international knowledge spill-overs. The parameters in the knowledge production function have been taken from Bottazzi and Peri (2007) who estimated them by means of econometric analysis using a sample of 15 OECD countries from 1973 to 1999. The first objective is to update these parameters using more up-to-date data and a broader set of countries.

Objective 2: Differentiate between public and private R&D within the knowledge production function

The current specification of the knowledge production function assumes that research conducted by businesses and the public sector (government and universities) has the same effect on creation of new ideas. However, the nature of public and private research efforts is quite different. Private companies invest mainly in applied research and development whilst public R&D typically concentrates on basic research. Therefore, the two types of investment may yield different impacts. The second objective is to expand the specification of the knowledge production function in order to accommodate potential differential impacts from private and public R&D.

Objective 3: Assess the complementarity/substitutability between public and private R&D

In principle, public R&D has a direct and indirect impact on knowledge creation. The direct impact is the new knowledge generated in government labs and the output of the research carried out by academic institutions (Objective 2). The indirect impact reflects the influence of government R&D policies and efforts, such as R&D grants and investment in basic research, on private R&D investment. The last objective of this report is to quantify the impact of public R&D on private R&D and, in particular, gauge the degree to which public R&D stimulates or crowds out private R&D.

The remainder of this report is structured as follows:

- Section 0 sets out the methodology used for each objective;
- Section 3 outlines the data used in the analysis; and
- Section 4 presents and discusses the results of the analysis.

2 Methodology

This section discusses the methodology used to address the three objectives, which involves the estimation of a series of econometric models. Due to the non-stationarity of the series under investigation and the nature of the underlying relationships, cointegrating and error correction models are used across all objectives. The models are estimated by panel Dynamic OLS (DOLS) although alternative methods have also been considered.

- **Objective 1.** Domestic stock of knowledge is modelled as a function of domestic R&D employment and international stock of knowledge.
- **Objective 2.** The standard production function (Objective 1) is expanded and re-estimated to allow for differential impact between public and private R&D.
- **Objective 3.** Business-funded R&D is modelled as a function of public-funded R&D whilst controlling for confounding effects.

2.1 QUEST III knowledge production function

Equation 1 describes the knowledge production function in QUEST III, which can be written as a log-linear restricted error-correction model (equation 2).[3]

$$\Delta \boldsymbol{A_t} = \boldsymbol{\nu A_{t-1}^{\phi} A_{ROW,t-1}^{\omega} L_{t-1}^{\lambda}} \qquad (1)$$

$$\Delta logA_t = log\, v + \gamma\left(logA_{t-1} + \delta\, log\, A_{ROW,t-1} + \mu logL_{t-1}\right) + \varepsilon_t \qquad (2)$$

where A and A_{ROW} denote the domestic and international stock of knowledge respectively, L is the level of domestic R&D employment, $\gamma = \phi$, $\delta = \omega/\gamma$, and $\mu = \lambda/\gamma$. The data required for the estimation of this equation is described in Section 3.

The expression in brackets in equation (2) reflects the long-run relationship between the underlying variables, and γ measures how quickly the domestic stock of knowledge responds to past disequilibrium, i.e. the speed of adjustment.[4]

This framework assumes that knowledge is generated by high-skilled workers working in the R&D sector and through international spill-over of ideas which expand the stock of usable knowledge. Both may serve to provide more opportunities to generate new ideas. Alternatively, as ideas are discovered it may become harder to find new ones suggesting that the effect of international stock of knowledge on domestically generated ideas could be negative.

The parameters of the knowledge production function in QUEST III have been taken from Bottazzi and Peri (2007) who estimated the parameters in equation (1) with panel cointegration and error correction models. The motivation of their approach was twofold:

- Due to the persistence or non-stationarity of the underlying time series, applications of conventional econometric techniques could lead to spurious regressions; and
- The underlying relationship is subject to significant time lags. For instance, an increase in domestic R&D employment is not expected to generate new knowledge instantaneously.

[3] Equation (2) is an approximation of equation (1) as $\Delta logA_t \neq \Delta A_t$.
[4] The parameters of interest in (1) depend on both the cointegrating vector and the speed of adjustment coefficient.

Cointegrating regressions allow estimation of long-run relationships whereas the error correction models provide insights into the short-run dynamics and adjustment mechanism to the long-run equilibrium (see Figure 1 for a short description of cointegration and error correction models).

Figure 1: Cointegration and error-correction models

Macroeconomic time-series often exhibit stochastic trends and have no tendency to revert to a mean, i.e. both their mean and variance are not constant (non-stationarity). It is well-known that estimating regression models with non-stationary series might produce spurious results, that is, obtain statistically significant relationships although the underlying variables are unrelated (Granger and Newbold, 1974).

Consistent with the existing time-series literature, Bottazzi and Peri as well as the analysis presented in this report adopt the following econometric strategy.

Testing for unit roots. A series is integrated of order one (I(1)) if its level is non-stationary but its first difference is stationary. Botazzi and Peri applied the Im, Pesaran and Shin (2003) and Pesaran (2003) panel unit root tests and concluded that "shocks to R&D and to the domestic or international stock of knowledge are very persistent and that these variables can be represented by non-stationary processes" (pp. 449).

Testing for cointegration. If two or more series are I(1), then their relationship is typically analysed within a cointegration framework (see, for instance, Hendry and Juselius, 2000). Two series are said to be cointegrated if there exists a linear combination of them that is stationary. The existence of cointegration implies that there is a long-run relationship between the series. Intuitively, if two time-series are cointegrated then there is an equilibrium relationship that ties the two series together in the long-run. In the short-run, there might be deviations from equilibrium but in the long-run the series move together. Botazzi and Peri applied the two Pedroni (1995) and seven Pedroni (1999) tests and rejected the null of no cointegration in seven out of nine cases.

Estimating cointegrating regressions. If the three series under investigation are cointegrated, the long-run relationship may be estimated using cointegrating regressions. Botazzi and Peri used the panel Dynamic OLS estimator of Mark and Sul (2003) which involves estimating the following equation:

$$\mathbf{logA_{i,t}} = \boldsymbol{\alpha_i} + \boldsymbol{\delta}\log \mathbf{A_{ROW,i,t}} + \sum_{s=-l_i}^{p_i} \boldsymbol{\delta_i}\,\Delta\log \mathbf{A_{ROW,i,t-s}} + \boldsymbol{\mu}\mathbf{logL_{i,t}} + \sum_{s=-l_i}^{p_i} \boldsymbol{\mu_i}\,\Delta\log \mathbf{L_{i,t-s}} + \epsilon_{i,t}$$

The $\boldsymbol{\delta}$ and $\boldsymbol{\mu}$ coefficients reflect the long-run elasticities of the international stock of knowledge and domestic R&D, respectively. Leads and lags of the differenced covariates are included in the regression to account for endogeneity among the series.

Estimating error-correction models. Error correction models (ECM) provide estimates of the short-run dynamics and the speed of adjustment to equilibrium. The following equations describe an ECM with one lag value for the first difference of $\mathbf{A}$, $\mathbf{A_{row}}$ and $\mathbf{L}$.

$$\Delta\log A_t = \alpha_1 + \beta_{11}\Delta\log A_{t-1} + \beta_{12}\Delta\log A_{ROW,t-1} + \beta_{13}\Delta\log L_{t-1} + \gamma_1(\log A_{t-1} - \theta_1\log A_{ROW,t-1} - \theta_2\log L_{t-1}) + u_{1t}$$

$$\Delta\log A_{ROW,t} = \alpha_2 + \beta_{21}\Delta\log A_{t-1} + \beta_{22}\Delta\log A_{ROW,t-1} + \beta_{23}\Delta\log L_{t-1} + \gamma_2(\log A_{t-1} - \theta_1\log A_{ROW,t-1} - \theta_2\log L_{t-1}) + u_{2t}$$

$$\Delta\log L_t = \alpha_3 + \beta_{31}\Delta\log A_{t-1} + \beta_{32}\Delta\log A_{ROW,t-1} + \beta_{33}\Delta\log L_{t-1} + \gamma_3(\log A_{t-1} - \theta_1\log A_{ROW,t-1} - \theta_2\log L_{t-1}) + u_{3t}$$

The $\boldsymbol{\beta}$ coefficients reflect the short-run dynamics whereas the $\boldsymbol{\gamma}$ coefficients measure the speed of adjustment. Botazzi and Peri found that only the domestic stock of knowledge responds to deviations from equilibrium ($\boldsymbol{\gamma_1}$is negative and statistically significant) whereas the international stock of knowledge and domestic R&D are weakly exogenous ($\boldsymbol{\gamma_2}$ and $\boldsymbol{\gamma_3}$ are statistically insignificant).

The results reported by Bottazzi and Peri suggest that:

- Both the international stock of knowledge and domestic R&D employment have positive and statistically significant effects on the domestic stock of knowledge;

- In general, R&D employment has a greater impact on the generation of new ideas than the international stock of knowledge. However, the estimated elasticities vary across alternative specifications;[5]

- International spill-overs appear to be more important for non-G7 countries (technology followers) whereas G7 countries (technology leaders) rely more on their own resources to generate new knowledge; and

- Deviations from the long-run equilibrium are persistent. The half-life of disequilibrium is about nine years. [6, 7]

2.2 Objective 1: Update the parameters in the knowledge production function

Following Bottazzi and Peri, the relationship between the domestic and international stocks of knowledge and R&D employment is estimated within a cointegration and error correction framework. The main differences between the analysis carried out in this report and Bottazzi and Peri are summarised below.

- **Country sample.** Bottazzi and Peri analysed fifteen major OECD countries whereas this report considers a wider set of countries (see section 3 for more details).

- **Time-series sample.** Bottazzi and Peri's sample covered the period from 1973 to 1999. On the basis of data availability, this report uses a more recent time period (annual data from 1985 to 2011).

- **Measure of innovation.** Bottazzi and Peri proxy innovation by the number of patents filed at the US Patent and Trademark Office (USPTO). The stock of knowledge used in the model is the accumulated patent count discounted by a depreciation rate (see section 3). It is well-recognised in the literature that patents filed at the USPTO or any individual country's patent office are subject to geographical bias. For example, inventors from the US or countries closer to the US are more likely to file patents at the USPTO (OECD, 2009). In this report, the primary patent measure is patent applications to the European Patent Office (EPO).[8]

The EPO was created in 1974 as a regional patent office to provide a single patent filing and grant procedure for member states of the European Patent Convention (EPC).[9] Once a patent has been granted by the EPO, it must be validated and kept in force in each country where protection is desired. Since the EPO is an international office, patent count is not biased towards a single country and hence it is less susceptible to geographical bias (Rassenfosse et al., 2013).[10]

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[5] The R&D elasticity ranges between 0.30 and 0.79 and the world stock of knowledge elasticity between 0.17 and 0.56.

[6] Half-life is the time required for 50% of the disequilibrium to be corrected.

[7] In a recent study, Bottasso et al. (2013) replicated the Botazzi and Peri analysis using a more up-to-date dataset, a different estimation technique and an alternative proxy for R&D. Bottasso et al. (2013) confirmed Bottazzi and Peri's main result, however, they find stronger spill-over effects from the international stock of knowledge and lower elasticities for R&D employment.

[8] A number of other measures have been considered. See Appendix 0 for a discussion around the pros and cons of these measures and the rationale for selecting EPO patents as the main proxy.

[9] EPO provides a cost-effective way to patent if the applicant is targeting more than three European countries for protection.

[10] However, European countries are more likely to patent at the EPO than non-European countries. Furthermore, Rassenfosse and van Pottelsberghe (2007) show that older members of the EPC have a higher propensity to file applications at the EPO.

2.3 Objective 2: Differentiate between public and private R&D within the knowledge production function

The knowledge production function in QUEST III does not differentiate between private R&D conducted by businesses and public R&D performed by governments or academic institutions. However, the nature and aim of public and private research efforts is quite different.

R&D is generally classified into basic research, applied research, and development, according to how close the research is to commercial applications.[11] Private companies invest in applied research and development whilst public R&D is typically concentrated in basic research, which happens earlier in the R&D cycle. The new ideas derived from applied research are often patented whereas the knowledge produced by basic research is mainly published in academic journals.

Within the knowledge production framework discussed in the previous section, public R&D may have a different impact than business R&D because (i) it involves different types of research and (ii) the underlying measure of innovation (e.g. patent applications to the EPO) used in the estimation of knowledge production function may omit a large portion of the knowledge generated by public investment, i.e. the part that is not patented.

In order to test the differential impact hypothesis, the knowledge production function in (1) is modified accordingly:

$$\Delta A_t = \nu A_{t-1}^{\phi} A_{row,t-1}^{\omega} L_{\mathrm{P,t-1}}^{\lambda_P} L_{\mathrm{B,t-1}}^{\lambda_B} \qquad (3)$$

where L_P is the level of R&D employment in the public sector and L_B is the R&D employment in the private sector. The estimation of (3) is carried out in the same way as in the case of the standard knowledge production.

2.4 Objective 3: Assess the complementarity/substitutability between public and private R&D

The previous objective aims to evaluate the direct impact of public R&D on knowledge creation. However, the research taking place at government labs and universities may complement private R&D efforts and therefore have an indirect impact. This section provides a methodological framework to evaluate this indirect impact and in particular to assess the degree to which public R&D investment stimulates or crowds out business R&D.

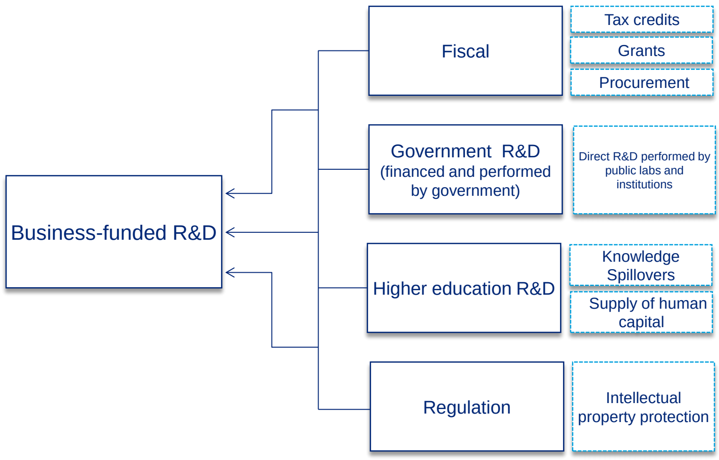
2.4.1 Context

The main focus of the analysis carried out under Objective 3 is on public R&D expenditure, which is largely comprised of: (i) procurement; (ii) grants; (iii) direct government R&D; and (iv) university R&D expenditure. Policy-makers have a number of other instruments available to influence private R&D including tax credits and intellectual property protection laws. However, these are beyond the scope of this report (tax incentives are analysed in Task 3).

[11] Basic research consists of experimental or theoretical work undertaken to acquire new knowledge whilst applied research is an original investigation directed towards a specific practical aim or objective which could be useful in developing or improving products, processes or services. The development stage involves a systematic work, drawing on existing knowledge gained from research and/or practical experience, directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed (OECD 1994).

In order to provide a broader context, the channels through which public R&D investment and policies could stimulate or substitute business R&D are illustrated in Figure 2 and discussed below (Becker, 2015; Guellec & Pottelsberghe, 2003; Kanwar and Evenson, 2002).[12]

Figure 2: Impact of government R&D and policies on private R&D



- **Fiscal policies.** Governments can utilise three fiscal policy instruments to affect business R&D: (i) Tax breaks[13]; (ii) procurement of public R&D projects to private companies; and (iii) grants that subsidise private R&D projects. Tax incentives and procurement are expected to have a positive impact on private R&D. Alternatively, the impact of grants may be positive by lowering the cost of R&D or zero if grants are used as a substitute for business funds.

- **Government-performed R&D.** Direct government spending on R&D may crowd out private spending by increasing the demand for R&D and hence its price. Goolsbee (1998) argues that because the majority of R&D spending is on salary payments and the supply of high-skill staff is inelastic, an increase in government spend will lead to an increase in wages. On the other hand, government spending mainly focuses on generating basic knowledge which may be adopted firms in applied research. In that sense, public investment could be conducive to private R&D.

- **Higher education R&D.** There are two key channels through which research conducted by universities could impact business R&D: (i) Universities generate knowledge that spills over into the private sector, increasing its R&D productivity (Nelson, 1986)[14]; and (ii) Universities improve a country's human capital, and because higher human capital tends to increase the rates of investment (Romer, 1991), education R&D stimulates private R&D.

- **Regulation.** Intellectual property protection laws incentivise R&D investment by guarding expected profits against imitation and free-riding.

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[12] There are two main arguments in favour of a business supportive R&D policy. The first one is related to the impact of R&D investment on innovation, productivity and economic growth. The second argument is based on market imperfection (Arrow, 1962) and that the amount being invested by companies is lower than the socially optimal level due to diffusion of knowledge beyond the control of the inventor and/or the high risks associated with R&D investment.

[13] Most OECD countries allow for a full write-off of current R&D expenditures, which implies that depreciation allowances are deducted from taxable income (Guellec & Pottelsberghe, 2003).

[14] The importance of the MIT for the development of Boston's high technology Route 128 and of Stanford University for the location of Silicon Valley is often cited as evidence of agglomeration and positive spill-over effects of university research on business R&D.

2.4.2 Empirical framework

The complementarity or substitutability between public and private R&D investment is evaluated by estimating the following model.

$$\boldsymbol{logS_{i,t}^{B} = \nu_i + \mu_1 logS_t^{GF} + \mu_2 logS_t^{GD} + \mu_3 logS_t^{HE} + \delta logX_{i,t} + \varepsilon_{i,t}} \quad (4)$$

where subscripts i and t indicate country and year, $S_{i,t}^{B}$ is business R&D investment funded and performed by business, $S_{i,t}^{GF}$ is R&D investment performed by business but funded by the government (grants and procurement), $S_{i,t}^{GD}$ is direct government expenditure and $S_{i,t}^{HE}$ is investment made by universities. Finally, ν_i are country fixed effects which capture time-invariant country-specific factors and $X_{i,t}$ is a set of controls. Government R&D complements private R&D if μ_1, μ_2 and μ_3 are statistically significant and greater than zero.

Equation (4) is driven by the discussion in the previous section, existing literature[15] and the availability of data.

- Granular data on grants and procurement are not available and their impact is evaluated jointly;
- Although quantifying the impact of tax credits is not within the scope of this analysis, its impact could be controlled for if sufficient data were available;[16] and
- Intellectual property protection may be proxied by the Ginarte-Park index (Park and Ginarte, 1997; Park, 2008) of patent rights which is available for several countries and over a long time period. However, there is little time variation in this variable and its impact is effectively captured by the fixed effects.

Control variables

Private R&D may be driven by several factors other than government R&D. If business and government R&D are influenced by common factors and these factors are not taken into account, then the estimated relationship may be biased.

- **Income.** Many studies in this strand of literature control for income or output measured by GDP. The rationale is that GDP may proxy for the availability of internal funds (internal finance factor) but also for the expected return from R&D investment (demand factor).
- **Availability of external finance.** The availability of external finance may also play a role. Wang (2013) and Kanwar and Evenson (2003) use interest rates as a proxy for this factor. In this report, the market capitalisation as a percentage of GDP is employed instead as this variable may also proxy for investors' expectation of future return on investment as well as economic uncertainty. As such, market capitalisation provides a parsimonious way to control for multiple possible factors.

[15] There is large body of research that has looked at the impact of government R&D and policies on private R&D investment. This research could be classified into micro and macro studies. The approach used in this report is based on the macro literature. The motivation is twofold. First, it is difficult to obtain micro data across several countries and over a sufficient time period to conduct the analysis. Second, a macro approach allows second-order effects of policies to be captured. For instance, an R&D subsidy could increase a firm's R&D but decrease competitors' activity by reducing the rate of return of their investment. Conversely, the recipient firm's research may generate knowledge spill-overs that could also be beneficial to its competitors (Guellec & Pottelsberghe, 2003). A summary of the macro literature is provided in Appendix 0.

[16] Tax credits are not expected to change frequently and as such they are not expected to be correlated with other regressors, therefore, the risk of omitted variable bias is relatively small.

- **Trade openness.** Several studies also control for trade openness (for instance, see Wang, 2013; Falk, 2006). The argument is that international knowledge is transmitted through trade and foreign direct investment (FDI), which increases the knowledge base and stimulates domestic R&D investment. Furthermore, trade openness may increase competition and put pressure on domestic companies to improve efficiency and R&D investment. Trade openness is captured by the sum of imports and exports as percentage of GDP.

- **Education.** A country with more people with tertiary education may tend to have more scientists and engineers and therefore may require greater levels of R&D investment. The supply of researchers is proxied by the percentage of people enrolled in tertiary education. This variable, however, could be correlated with higher education R&D investment, making difficult to disentangle their individual effects.

There are several other factors that previous studies have controlled for (see Appendix 0) but not considered in this report. This is justified by the following reasons:

- Studies that analyse developing countries include variables that reflect political stability and institutional factors. However, these factors are broadly stable in the developed countries analysed here whilst any time-invariant cross-country differences are captured by fixed effects.

- Other factors considered include, for instance, number of researchers, share of industrial production and fixed capital formation. Although these factors might be correlated with R&D investment, it is unlikely that they have a causal effect.

- Finally, to avoid the problem of multicollinearity, a parsimonious modelling strategy has been adopted.

Estimation

Similar to the previous two objectives, equation (4) is estimated by panel DOLS given the non-stationarity of R&D investment but also the significant time lags involved in the underlying relationship. For example, it typically takes a significant amount of time for R&D investment to translate into new ideas. Furthermore, the knowledge created by government and universities is expected to slowly diffuse into the private sector.

DOLS is designed to account for possible endogeneity between business R&D and the control variables. For instance, equation (4) assumes that income affects R&D investment, but, R&D investment also drives economic growth. Endogeneity is controlled for by including leads and lags of the first difference of the regressors in equation (4).

2.5 Key challenges

This section discusses the key challenges and possible mitigations associated with the estimation of the relationships discussed in the previous sections. The focus is on the following four methodological and modelling aspects:

- Measuring innovation (Objective 1 and 2);
- Controlling for time-series variation in propensity to patent (Objective 1 and 2);
- Power of cointegration tests (all three Objectives); and
- Collinearity between private and public R&D employment (Objective 2).

Measuring innovation

Proxying innovation by the number of patents has a long tradition in applied economics (Griliches, 1990). However, it is also widely recognised that patent proxies have significant limitations. Not all new ideas are patented and not all patents reflect innovative ideas. Furthermore, the quality of ideas cannot be captured by the count of patent applications as some patents contain more relevant ideas than others. Bottazzi and Peri argue that this may not be a significant limitation of patent data since each unit of observation (country/year) aggregates a large number of patents, and differences in the quality of ideas for individual patents are likely to be averaged out. Despite its limitations, patent data are generally considered as the best proxy of output of innovative activities (Nagaoka et al., 2010).

Mitigation: The sensitivity of the results presented in this report is examined by considering trademarks as an alternative proxy of innovation. The main advantage of trademarks is that while patents are more prevalent in the science and technology sectors, trademarks are common across a variety of industries. The main drawback, however, is that not all trademarks represent new products or innovation (Madsen, 2008).

Variation in propensity to patent

The R&D-patents relationship has two dimensions. Research efforts lead to inventions (a knowledge production effect) and inventions lead to patents through a propensity to patent effect (Rassenfosse and Pottelsberghe, 2009). If propensity to patent varies over time then the relationship estimated using the standard knowledge production specification would omit the propensity to patent effect and induce bias in the estimation.

Table 1 sets out five key factors that may lead to differences in propensity to patent over time and across countries. In particular, a strong patent system is expected to be conducive to patenting. Economies that specialise in specific sectors, such as computing and pharmaceuticals, or are dominated by large companies are expected to have higher tendency to patent. Furthermore, the propensity to patent may vary across local and international offices. For instance, the internationalisation of business may have increased the tendency to patent at the EPO and reduced the tendency to file patents at local offices. Finally, fees paid to patent offices to process patent claims have been shown to affect inventors' decisions to patent with specific offices (Rassenfosse and Pottelsberghe, 2010).

Mitigation: While most of these factors are expected to be relatively stable over time and could be captured by the fixed effects, the increased internationalisation of the world's economies over the last three decades and the steep drop in the EPO fees in the mid-90s (Rassenfosse and Pottelsberghe, 2010) may have had a significant impact on the propensity to patent. In order to control for these two factors, alternative specifications of the standard knowledge production function that include proxies of international trade and patent fees have been estimated.

Table 1: Sources of variation in propensity to patent

Source	Description	Cross-country variation	Time-series variation
Strength of patent system	Patentability of subject matter, restrictions on patent rights, and enforcement mechanisms	Low across developed countries; medium/high for developing countries	Low for developed countries; medium/high for developing countries
Industry composition	Ideas generated by specific industries like high-tech are more "patentable" than other sectors like services	High	Low
Internationalisation	Companies involved in international business are more likely to make applications at international rather than local patent offices	Medium/High	Medium/High
Company size	Empirical evidence from micro studies suggest that smaller firms have lower tendency to patent	Medium/High	Low
Fees	Administrative fees paid to the patenting office to process patent claims	Low/Medium	Medium/High

Power of cointegration tests

Cointegration tests suffer from low power in finite samples, in other words, they have the tendency to under reject the null hypothesis of no cointegration when false more often than predicted by the asymptotic distribution theory (Pesaran, 2015). Following Botazzi and Peri and related literature, the cointegration hypothesis is tested within a panel framework. Pooling data across countries could be viewed as drawing repeated observations from the same distribution, increasing the sample size and therefore the power of the test (Baltagi and Kao, 2000).

Notwithstanding this, panel cointegration tests have their own limitations (Caporale and Ceratto, 2006). In many cases, their asymptotic distribution is derived under the assumption that the error terms are not cross-correlated. If this assumption is violated, the tests are inconsistent. Furthermore, the assumption of homogeneity across cross-sectional units required by many cointegration tests is often too restrictive. Finally, in the presence of structural breaks, panel tests like their time-series equivalents have low power.

Mitigation: A number of alternative cointegration tests that rely on different assumptions have been applied to deal with the panel cointegration test limitations. Alternative sample periods have also been considered to mitigate the risk associated with structural breaks.

Collinearity between private and public R&D

Private and public R&D are highly correlated, which makes it difficult to isolate their individual impact on innovation.[17] Collinearity is challenging to deal with as it requires either a large sample (in principle, collinearity is a problem in small or finite samples) or to impose restrictions on some the coefficients of the collinear variables. The former involves more data and the latter requires prior information on the underlying information. Both of them are not available for this report.

[17] The correlation is c.0.80. See Appendix 0.

Furthermore, since public R&D focuses mainly on basic research, its impact might be subject to longer time lags than what the model could identify.

Mitigation: Number of publications, which is correlated with public R&D and observed later in the R&D cycle, could mitigate the challenge associated with the long-time lags.

3 Data

Table 2 summarises the data used in the econometric analysis. The European Patent Office (EPO) and Patent Cooperation Treaty (PCT) data have been obtained from the OECD and measure patent applications by inventor's country of residence and priority year.[18] The worldwide proxy developed by Rassenfouse et al. (2013) is similar to the EPO and PCT measures. However it captures patent applications at both international (EPO or WIPO[19]) and local offices. These patent count data have been used to construct the stock of knowledge variable as described in Figure 3.

R&D employment measures the number of employees working in the R&D sector. Data are available by type of employee, i.e. researcher, technician and other support staff. The analysis for Objectives 1 and 2 primarily uses number of researchers as a proxy for high-skilled workers on the basis that research staff is more closely linked to the production of new knowledge than supporting staff.[20] However, the sensitivity of the results has been tested across alternative measures (total R&D personnel and R&D expenditure).[21]

Objective 3 relies on R&D data on gross domestic expenditure. Unlike R&D employment data, R&D expenditure is further disaggregated by source of funds (e.g. business or government) which is used to assess the complementarity/substitutability of public and private R&D.

Other control variables used in the econometric models are also set out in Table 2: Data summary.

[18] Priority year measures the year of first filing of a patent application anywhere in the world, whereas grant date reflects the date that a patent office issues a patent for an invention. Given the lag between the time an application is made and granted, priority date is a more accurate measure of the time when an idea was generated. Furthermore, inventor's country of residence rather than applicant's country of residence is preferred as it is a closer measure of where the invention came from.

[19] World Intellectual Property Organisation

[20] "Researchers are professionals engaged in the conception or creation of new knowledge, products, processes, methods and systems and also in the management of the projects concerned" (Frascati Manual, OECD 2002, pp. 301)

[21] R&D series for some countries contain gaps which have been filled by linearly interpolation.

Table 2: Data summary[22]

Variable	Proxy	Description	Source
Patents	EPO	Patent applications to the European Patent Office by inventor's country of residence and priority date	OECD
	PCT	Patent applications filed under the Patent Cooperation Treaty by inventor's country of residence and priority date	OECD
	Worldwide	Patent applications filed by inventor's country of residence and priority date at international and local patent offices	Rassenfouse et al. (2013)23
Trademarks	Trademark applications	Trademark applications filed directly with national intellectual property offices as well as under the Madrid System	WIPO
R&D	Researchers	Number of researchers employed in the R&D sector disaggregated by business, government and higher education sectors of performance	Eurostat, OECD
	Total personnel	Total personnel employed in the R&D sector including researchers, technicians and additional support staff	Eurostat, OECD
	Gross domestic expenditure	Total domestic expenditure in R&D	Eurostat, OECD
	Gross domestic expenditure by source of funds	Includes business expenditure funded by business, business expenditure funded by government, government expenditure funded by government as well as total higher education expenditure	OECD
Publications	Scientific and technical journal articles	The number of scientific and engineering articles published in STEM disciplines	World Bank
Control variables	Patent fees	Sum of fees that must be paid during the first 18 months from the filing date	Rassenfouse et al. (2015)24
	Exports	Total exports of goods and services	World Bank
	GDP per capita	Average GDP per person in the economy	OECD
	Trade openness	Sum of imports and exports measured as a share of GDP	World Bank
	Market capitalisation	Market value of domestically listed companies	World Bank
	Education	Ratio of total tertiary enrolment to the total population of the relevant age group	World Bank

[22] Data plots and summary statistics have been generated to sense-check the data. However, the quality of the information provided by different sources cannot be evaluated.

[23] http://gder.phpnet.org/rassenfosse/paper_The_worldwide_count_of_priority_patents.html
[24] http://gder.phpnet.org/rassenfosse/data.html

Figure 3: Stock of knowledge ($\mathbf{A}$)

The domestic stock of knowledge is constructed to capture the accumulated knowledge within a country and is the dependent variable in the knowledge production function. Consistent with Botazzi and Peri (2007) and other related literature, the stock variable is constructed as the depreciated cumulative sum of patent applications for a given country, such that:

$$\mathbf{A_{i,t+1}} = \mathbf{Patent\ Applications}_{\mathbf{i,t}} + (\mathbf{1} - \boldsymbol{\delta}) * \mathbf{A_{i,t}}$$

Where $\mathbf{A_{i,t}}$ refers to the domestic stock of knowledge for country $\mathbf{i}$ at time $\mathbf{t}$. The initial value, $\mathbf{A_{i,t_0}}$, is constructed using the perpetual inventory method, such that:

$$\mathbf{A_{i,t_0}} = \frac{\mathbf{Patent\ Applications_{i,t_0}}}{\mathbf{g_i} + \boldsymbol{\delta}}$$

The growth rate for each country, $\mathbf{g_i}$, is calculated as the average annual growth rate of patent applications in the time period from $(\mathbf{t_0})$ to$(\mathbf{t_0} + \boldsymbol{\tau})$. The value of $\boldsymbol{\tau}$ is set at 10 such that, the growth rate of patenting is calculated between $(\mathbf{t_0})$ to$(\mathbf{t_0} + \mathbf{10})$.25 The depreciation rate, $\boldsymbol{\delta}$, is the rate at which new ideas depreciate and is set at 10% as in Bottazzi and Peri.26
The international stock of knowledge, $\mathbf{A_{ROW}}$, is constructed for each country as the sum of the stock of knowledge in all other countries in a given year.

Country sample

A total of 41 EU and/or OECD countries have been considered in the analysis. Based on the time-series availability of the key variables (patents and R&D), these countries have been classified into three samples.

- **Sample 1:** High-income OECD countries for which there is data available for a long time-series (c. 30 years).[27]
- **Sample 2:** Countries for which the maximum time span of the sample is up to 20 years.
- **Sample 3:** Countries for which insufficient time-series data (less than 15 years) is available to be considered in the cointegration analysis.[28]

The countries within each of the three samples are shown in the figure below.

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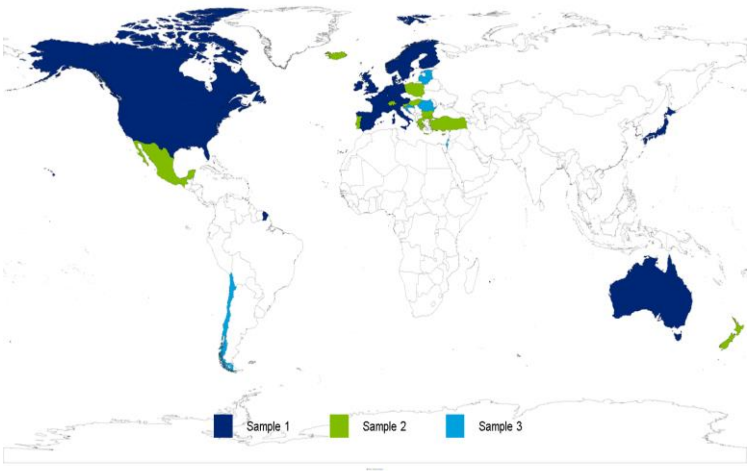
[25] Bottazzi and Peri set this value at 5, however, for the purpose of this analysis a larger window used for calculating the growth rate may mitigate potential issues associated with the large time variation in patenting over the initial years of the analysis. The sensitivity of the results to the stock parameters has been analysed and presented in the Appendix.
[26] This value has been set at 10% in line with the related literature. However, alternative values have been used as part of the sensitivity analysis. See Appendix 0 for more details.
[27] This sample is similar to the one used by Bottazzi and Peri (2007), with the inclusion of Belgium and Austria.
[28] The small sample properties of cointegration tests and estimators have been examined by Breitun et al. (2008) and Pedroni (2004)

Figure 4: Country samples

Sample 1	Sample 2	Sample 3
Australia	Bulgaria	Chile
Austria	Cyprus	Croatia
Belgium	Czech Republic	Estonia
Canada	Greece	Israel
Denmark	Hungary	Latvia
Finland	Iceland	Lithuania
France	Korea	Luxembourg
Germany	Mexico	Malta
Ireland	New Zealand	Romania
Italy	Poland	
Japan	Portugal	
Netherlands	Slovak Republic	
Norway	Slovenia	
Spain	Switzerland	
Sweden	Turkey	
United Kingdom		
United States		



3.1 Descriptive analysis

This section summarises the key insights obtained from a descriptive analysis.

- **The stocks of knowledge implied by EPO patent applications have grown significantly over the period analysed (Figure 5).** For example, the German stock of knowledge has increased by 150% over the period from 1985 to 2011. The growth in the stock of knowledge implied by EPO patents is considerably higher than that implied by the USPTO patents used by Bottazzi and Peri (2007). This difference may be associated with the higher tendency for businesses to protect their inventions in multiple countries and therefore file applications at international offices.

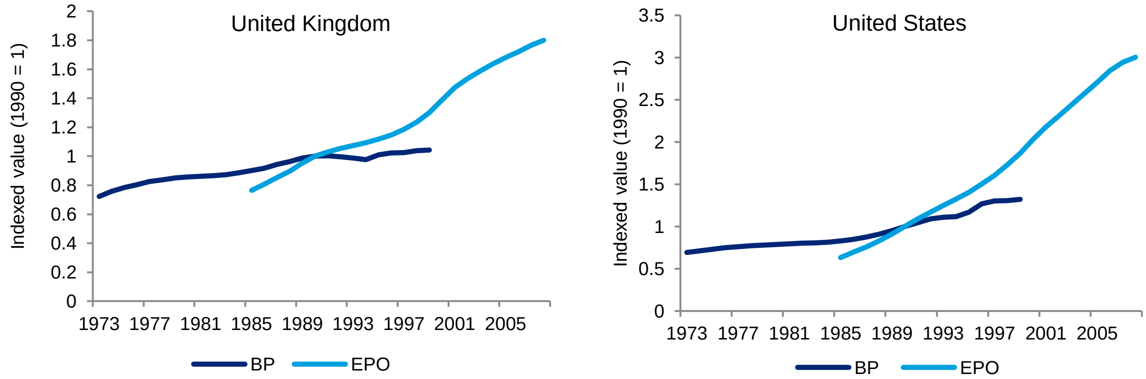
- **The number of people working in R&D has also grown significantly (Source:** OECD; Bottazzi and Peri (2007) Deloitte calculations

- **Figure 6).** This is the case for R&D employment in both the private and public sector. Non-G7 countries though have experienced a much higher growth in public sector R&D employment relative to private sector. Furthermore, government expenditure as percentage of total R&D investment has risen in both G7 and non-G7 countries.

- **The US together with Germany and Japan account for c.64% of world patents applications and c.55% of world R&D employment (Figure 7).**[29] The US with 29% of world's patent applications is the technology leader. Germany and Japan are also on the technology frontier accounting for 19% and 17% of total patent applications. Other G7 countries typically contribute less than 5% to the total stock of patents whereas the remaining countries within the sample are lagging significantly behind the major economies (the only exception being South Korea).[30]

- **The innovation gap between G7 and non-G7 countries has narrowed over time (Figure 8).** While the G7 countries accounted for 85% of patent applications in 1981 this number has decreased to 78% in 2011. Similarly, the share of G7 R&D workers has declined from 85% in 1981 to 71% in 2011.

Figure 5: EPO vs. USPTO trends



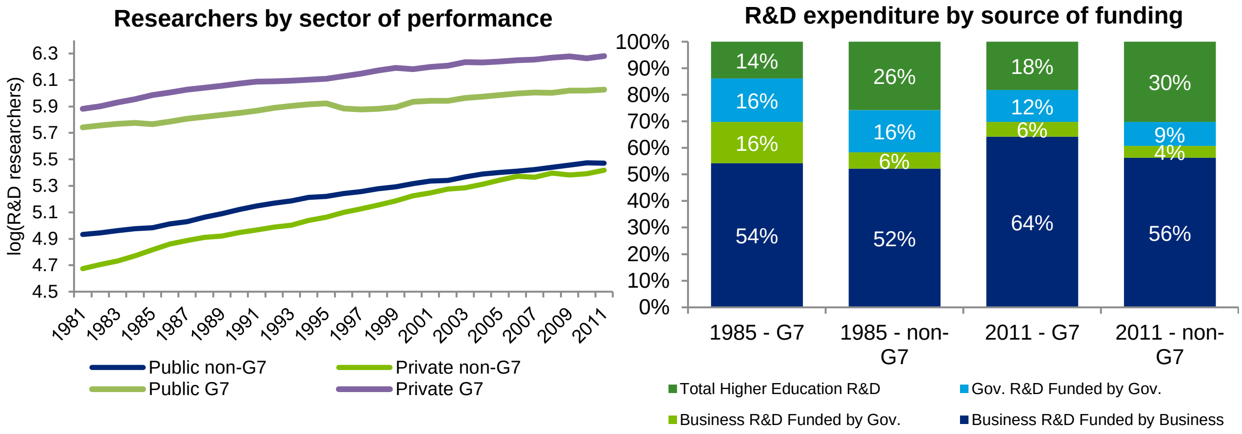
Source: OECD; Bottazzi and Peri (2007) [31] Deloitte calculations

[29] The patent and employment shares are for 2005 and relative to the 42 countries within the sample.

[30] The ratio of patents to researchers varies across countries. For example, in 2005 Germany filed approximately 9 patents per 100 researchers whereas the US filed approximately 3 patents per 100 researchers. This may indicate varying level of R&D productivity, which could be partly captured by the fixed effects in the econometrics estimation.

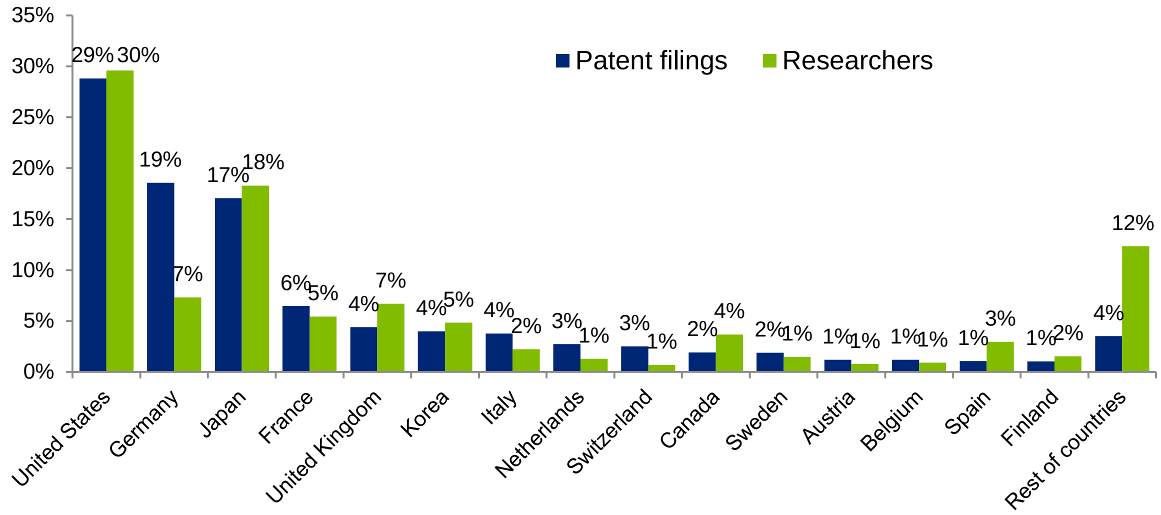
[31] USPTO patent count are the same data used by Bottazzi and Peri's data (BP) have been supplied by Carolina Castagnetti from Bottassso et al. (2013) who replicated the original analysis of Bottazzi and Peri.

Figure 6: Public and private R&D



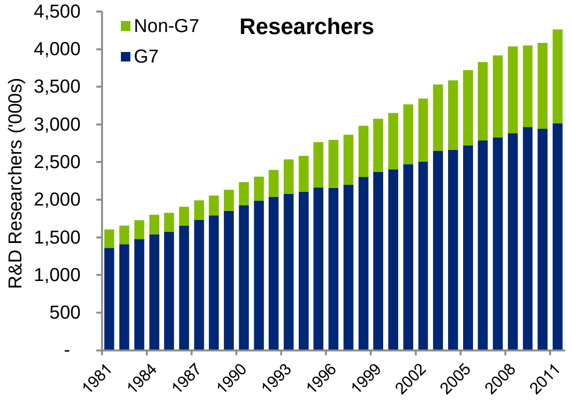
Source: OECD, Eurostat and Deloitte calculations

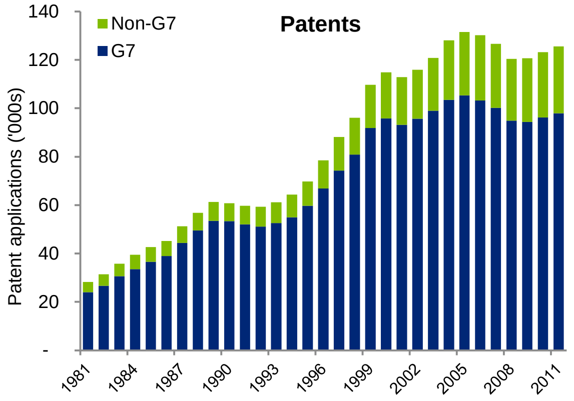
Figure 7: Percentage of patent filings and R&D researchers in 2005



Source: OECD, Eurostat and Deloitte calculations

Figure 8: Narrowing innovation gap between G7 and non-G7 countries





Source: OECD, Eurostat and Deloitte calculations

4 Results

4.1 Objective 1: Update the parameters in the knowledge production function

This section sets out the econometric estimates of the parameters in the knowledge production function. Three types of estimates are presented:

- Cointegration test statistics;
- Long-run elasticities; and
- Error correction term estimates.

In summary, the results suggest that:

- Although the evidence on the existence of cointegration is relatively mixed, the more powerful Westerlund (2007) tests suggest that the three underlying series may form a cointegrating relationship;
- R&D and international knowledge have statistically significant impacts on the creation of new ideas. Both effects appear to have contributed to the process of innovation in the last two to three decades;
- The estimated elasticity of R&D typically ranges between 0.5 and 0.7 and is lower than the international spill-over effect which usually ranges between 0.8 and 1;
- However, the estimated effects vary across countries. The split-sample approach indicates that G7 countries have benefited more from the international transmission of knowledge than the non-G7 countries. Conversely, non-G7 countries have relied more on their own R&D resources to generate new ideas than G7 countries; and
- The error correction coefficient typically ranges from -3% to -12%, which is generally consistent with the Bottazzi and Peri estimate of -7%.

Cointegration tests

Three types of panel cointegration tests have been considered.

- **Pedroni (1999, 2004).** These tests extend the Engle-Granger (1987) test to panels and test the residuals of the first stage regression between the levels of the underlying series for unit root.
- **Kao (1999).** This test follows the same approach as the Pedroni tests and allows for panel specific intercepts and homogeneous coefficients in the first-stage regression.
- **Westerlund (2007).** Unlike the residual-based Pedroni and Kao tests, the Westerlund test is based on an error correction approach. Furthermore, these tests allow for more general forms of dependence across cross-sectional units.

Table 3 presents the results of the cointegration tests. While the Pedroni tests overwhelmingly fail to reject the null of no cointegration, the Kao test rejects the null across the majority of the samples considered. The only exception is Sample 2 for which the time series span of the data is shorter. The Westerlund tests provide mixed results, however, they reject the null of no cointegration more often than not.

Based on several Monte Carlo simulations, Westerlund (2007) conclude that the error-correction based tests are more powerful than the residual-based tests of Pedroni. Gutierrez (2003) also provides Monte Carlo evidence suggesting that Kao's test outperforms Pedroni's tests when the time dimension of the panel is relatively small. As such, the results reported here are viewed as evidence in favour of the existence of cointegration.

A number of additional specifications encompassing different lag lengths as well as sample periods have been tested and suggest the same mixed results as reported in Table 3.

Table 3: Cointegration test results

Test	Version	Sample 1	Sample 1 and Sample 2	Sample 2	Start: 1990 End: 2011
Pedroni test (1999, 2004)	Panel v-Statistic	-0.14	1.26	1.01	2.14**
	Panel rho-Statistic	1.64	2.06	1.39	0.87
	Panel PP-Statistic	0.98	0.79	0.46	-0.27
	Panel ADF-Statistic	-0.24	-0.81	-0.65	-0.87
	Group rho-Statistic	3.38	3.18	1.05	2.42
	Group PP-Statistic	2.54	1.02	-1.21	0.6
	Group ADF-Statistic	0.19	-1.49*	-2.38***	-0.52
Kao test (1999)	Residual Cointegration Test	-2.61***	-2.7***	-0.9	-1.89**
Westerlund tests (2007)	Group t-Statistic	-1.89	-2*	-2.29	-2.2**
	Group a-Statistic	-5.86***	-6.21***	-7.13*	-4.88***
	Panel t-Statistic	-3.91	-7.23	-4.1	-10.25***
	Panel a-Statistic	-3.2*	-6.34**	-6.79**	-8.2***

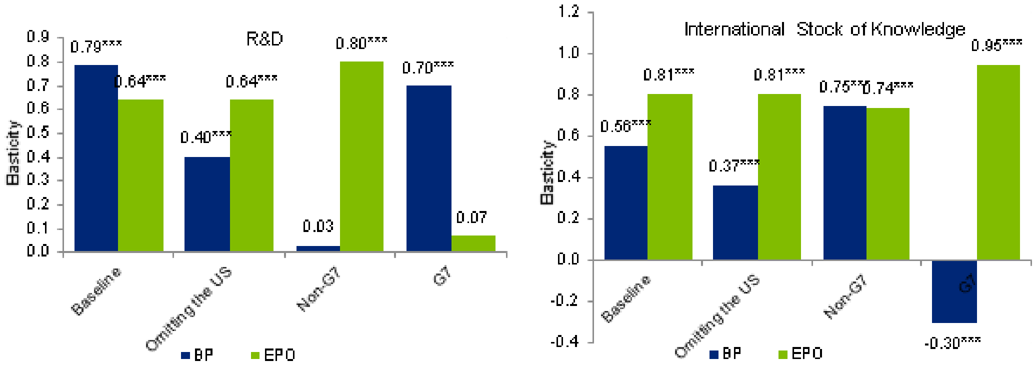
Source: Deloitte analysis

*Notes: Null hypothesis is no cointegration. Sample 2 countries with less than 20 years' worth of data were omitted from the Westerlund tests. *** , **, * indicate rejection of the null at 1%, 5% and 10%, respectively*

Long-run relationship – Sample 1

Figure 9 displays the long-run elasticities of the impact of R&D employment and international stock of knowledge on domestic stock of knowledge along with the Bottazzi and Peri estimates. The model has been estimated across the four samples used by Bottazzi and Peri.

Figure 9: Knowledge production function elasticities



Source: Bottazzi and Peri (2007) and Deloitte analysis

*Notes: Dependent variable: log domestic stock of knowledge; *** , **, * indicate statistical significance at 1%, 5% and 10%, respectively; BP are the Bottazzi and Peri (2007) DOLS estimates; EPO indicate the DOLS estimates obtained using the EPO patent count using Sample 1 countries from 1985 to 2011;*

The results suggest that:

- Both international knowledge spill-overs and domestic R&D have positive and statistically significant effect on domestically generated ideas;
- The impact of the international stock of knowledge is higher than that of R&D, although the hypothesis that the two elasticities are equal cannot be rejected in several specifications. This suggests that the international diffusion of knowledge over the last two or three decades has played a pivotal role in the innovation process;
- The results remain unaffected when the US, the largest innovator, is excluded from the sample. This is in contrast to the estimates provided by Bottazzi and Peri who found a significant reduction in their coefficient estimates when the US was excluded. The difference in the results may be explained by the presence of geographical bias and greater tendency of US inventors to apply to the USPTO;
- The relative impact of the underlying variables varies across the other two samples of countries. It appears that R&D has been more important for technology followers (non-G7 countries) than technology leaders (G7). This may reflect diminishing returns in R&D investment. The results for the international spill-overs show the opposite pattern with G7 countries benefiting from international knowledge more than the non-G7 countries; and
- An asymmetric impact has also been reported by Bottazzi and Peri but in the opposite direction. Bottazzi and Peri found that R&D is more important for G7 whereas international spill-over effects are more prominent for non-G7 countries. The difference between the two studies may be explained by the difference in the time periods analysed and/or the different patent measure.[32]

Long-run relationship - Sensitivity analysis

Table 4 reports the results of a series of sensitivity analyses. Overall, the results are broadly stable across alternative model specifications, estimation methods and sample

[32] The estimation technique as well as the proxy of R&D employment is the same in the two studies.

periods. The main exception is the estimates obtained from alternative measures of innovation and when a linear trend is included in the model.

- **Measure of innovation.** The baseline results use patents filed at the EPO. Three alternative measures of innovation have also been utilised: patents filed under PCT, worldwide patents and trademarks. The results obtained from these measures are noticeably different from the baseline results. R&D is statistically insignificant (the results with PCT indicate significance only at 10% level) whilst international stock of knowledge exhibits strong and significant effects. These perhaps counter-intuitive results together with the limitations of the three alternative measures discussed in Appendix 0 suggest that more weight should be placed on the EPO/baseline results.

- **R&D Proxy.** The sensitivity of the results has been examined across alternative measures of R&D. When only private R&D researchers are used in the model (baseline model uses both private and public workers) the elasticity of R&D decreases, whereas when R&D is proxied by total personnel employed in the R&D sector, the impact of R&D increases. The elasticity of international stock of knowledge is somewhat lower in the model that uses R&D expenditure.

- **Controls.** Controlling for possible time variation in propensity to patent at the EPO with exports leads to a noticeable decrease in the elasticities of both R&D and international stock of knowledge. Inclusion of EPO fees in the knowledge production function makes no difference in the estimates. Finally, a model with country-specific time trends has been estimated to control for potential unobserved time effects. The trend specification provides R&D estimates which are statistically insignificant. This specification should be interpreted with care as the results might be driven by the collinearity between the trend and R&D.

- **Estimator.** The model has been also estimated with the Fully Modified OLS (FMOLS) and Pooled Mean Group (PMG) estimators. Both provide estimates broadly similar to the DOLS estimator (baseline).[33]

- **Sample period.** The sensitivity of the results has been examined across alternative sample periods with the aim to investigate potential structural breaks in the underlying relationship. In order to preserve enough time-series observations, three samples have been considered. The first sample excludes the recent financial crisis, the second considers only data from the 1990 onwards, and the third one data from 1990 to 2007. The results do not appear sensitive to the sample period used.

- **Lag/lead specification.** The lag/lead specification in the baseline DOLS model has been selected on the basis of Bayesian Information Criterion (BIC).[34] Alternative specifications provide similar results to those obtained from the baseline model.

[33] FMOLS modifies the OLS estimator to account for serial correlation and endogeneity. FMOLS is asymptotically equivalent to DOLS but DOLS has better finite sample properties (Kao and Chiang, 2000). PMG is based on an unrestricted error correction model and allows for country heterogeneity in the short-run dynamics but imposes the same long-run cointegrating relationship across all countries. PMG requires a relatively large time period (and T to be greater than N) in order to provide reasonable country-specific estimates.

[34] This is the approach that is recommended in the literature (Westerlund, 2005).

Table 4: Knowledge production function sensitivity analysis

Model category	Model	R&D	International Stock of Knowledge
Baseline		0.64***	0.81***
Measure of innovation	PCT	0.49*	1.07***
	Worldwide patents	-0.12	0.76***
	Trademarks	-0.38	1.67***
R&D Proxy	Private researchers	0.41***	0.85***
	Total personnel	1.07***	0.76***
	Total R&D Expenditure	0.65***	0.55***
Controls[35]	Fees	0.67***	0.7***
	Exports	0.41***	0.43***
	Country specific time-trend	0.07	0.99***
Estimator	FMOLS	0.67***	0.77***
	PMG	0.63***	0.98***
Time period	1985 to 2007	0.6***	0.83***
	1985 to 2011	0.64***	0.81***
	1990 to 2007	0.73***	0.79***
	1990 to 2011	0.63***	0.82***
Lag/lead specification	2 lags and 2 leads	0.76***	0.73***
	2 lags and 1 lead	0.61***	0.85***
	1 lag and 2 leads	0.6***	0.86***
	1 lag and 1 lead	0.56***	0.88***

Source: Deloitte analysis

*Notes: Dependent variable: log domestic stock of knowledge; *** , **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS with the exception of the FMOLS and PMG results;*

Long-run relationship - Sample 2

Table 5 sets out the estimates of the knowledge production function by incorporating the countries within Sample 2 in the analysis. Some of the results presented in the previous sections using Sample 1 countries are also displayed for ease of comparison. Overall, six alternative country samples are considered:

(i) Sample 1 (17 countries);
(ii) G7;
(iii) Sample 1 non-G7 (10 countries);
(iv) Sample 1 and Sample 2 (32 countries);
(v) Sample 2 (15 countries); and
(vi) Sample 1 and Sample 2 non-G7 (25 countries)

In addition, three alternative specifications have been estimated: (i) Baseline; (ii) Personnel where R&D is proxied by total R&D personnel instead of researchers; and (iii) Exports which controls for the value of exports.

Given the shorter sample period available for Sample 2 countries, the results should be viewed as indicative.

[35] The coefficient of fees is -0.073 and insignificant and the coefficient of exports is 0.487 and significant at the 1% level in the respective models.

- The impact of R&D increases when the Sample 2 countries are included in the model. The international spill-over effect is typically lower but remains broadly close to one.

- The comparison between Sample 1 non-G7 and Sample 2 countries suggest that the impact of R&D and international spill-overs is quite similar in these two samples. The results for the G7 countries are closer to the results obtained for all other samples when R&D employment is proxied by total personnel.

Table 5: Sample 2 knowledge production function elasticities

Model specification	Sample	R&D	International Stock of Knowledge
Baseline	Sample 1	0.64***	0.81***
	G7	0.07	0.95***
	Sample 1 - Non-G7	0.8***	0.74***
Baseline incl. Sample 2	Sample 1 and Sample 2	1.02***	0.72***
	Sample 2	0.92***	1.13***
	Sample 1 and Sample 2 - non-G7	1.02***	0.77***
Total personnel	Sample 1	1.07***	0.76***
	G7	0.82***	0.81***
	Non-G7	1.2***	0.69***
Total personnel incl. Sample 2	Sample 1 and Sample 2	1.16***	0.86***
	Sample 2	0.98***	1.29***
	Sample 1 and Sample 2 - non-G7	1.1***	0.95***
Exports	Sample 1	0.41***	0.43***
	G7	-0.15	0.82***
	Non-G7	0.5**	0.5**
Exports incl. Sample 2	Sample 1 and Sample 2	0.84***	0.64***
	Sample 2	0.33**	1.86***
	Sample 1 and Sample 2 - non-G7	0.76***	0.86***

Source: Deloitte analysis

*Notes: Dependent variable: log domestic stock of knowledge; *** , **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS;*

Error correction models

Table 6 sets out the estimates of the error correction term described in equation (2).[36] These results are estimated by system GMM (Arellano and Bover, 1995; Blundell and Bond, 1998). The error correction term is the residuals from the DOLS regression detailed in the previous sections.

- The error correction coefficient typically varies from -3% to -12%. This variation is mainly a function of the country sample rather than model specification or sample period considered.

[36] The error correction term or speed of adjustment is the $\gamma 1$ coefficient discussed in Figure 1.

- Across the four alternative model specifications, the inclusion of Sample 2 countries leads to a greater speed of adjustment.

- Overall, the results are consistent with the results reported by Bottazzi and Peri who estimated a speed of adjustment of around 7%.

Table 6: Error correction term estimates

	Baseline	Total R&D Personnel	Exports	Start: 1985 End: 2007
Sample 1	-0.027***	-0.036**	-0.033***	-0.026***
G7	-0.015	-0.025	-0.005	-0.013*
Sample 1 - No G7	-0.037***	-0.043***	-0.034**	-0.036***
Sample 1 and Sample 2	-0.053**	-0.074**	-0.086**	-0.086***
Sample 2	-0.082**	-0.092**	-0.122**	-0.118***
Sample 1 and Sample 2 - No G7	-0.063**	-0.077**	-0.1**	-0.096***

Source: Deloitte analysis

*Notes: ***, **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by System GMM*

4.2 Objective 2: Differentiate between public and private R&D within the knowledge production function

Table 7 presents the estimates of the knowledge production function allowing for differential impact of public and private R&D. Two alternative proxies of public R&D are used: (i) number of researchers working in government R&D and universities; and (ii) number of publications.

- When public R&D is proxied by researchers, its coefficient is statistically insignificant whereas when it is proxied by publications the elasticity is approximately 0.4. Private R&D is statistically significant in both cases with an elasticity also close to 0.4.

- The specification which includes an interaction term provides statistically insignificant effects for both public and private R&D.

- The coefficient of international stock of knowledge remains relatively stable at around 0.8.

- These results should be interpreted with caution given the high correlation between the different R&D proxies (see Appendix for more details).

Table 7: Public & Private R&D estimates – Sample 1

Model	Total R&D	Private R&D	Public R&D	Publications	International Stock of Knowledge
Total R&D	0.64***				0.81***
Private		0.41***			0.85***
Public researchers and Private		0.37***	0.0		0.88***
Publications and Private		0.32***		0.39***	0.78***
Publications and Private and Interaction		0.03		-0.04	0.66***

Source: Deloitte analysis

*Notes: Dependent variable: log domestic stock of knowledge; ***, **, * indicate rejection of the null at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS*

Table 8 presents the results across different samples with public R&D proxied by number of publications.

- For the G7 countries, the private R&D elasticity is almost twice as large as that of public R&D. For non-G7, the opposite is observed, public R&D is more important than private (the latter is typically statistically insignificant).
- Furthermore, private R&D performed by G7 countries appears now to be more import than international spill-overs in generating new knowledge. For non-G7 countries, the results indicate that international spill-overs play a more significant role in the innovation process. This asymmetry between technology leaders and followers is noticeably different compared to the asymmetry observed in the standard knowledge production function specification.

Table 8: Public & Private R&D estimates – Sample 1 & Sample 2

Sample	Private R&D	Publications	International Stock of Knowledge
Sample 1	0.32***	0.39***	0.78***
G7	0.75***	0.44***	0.56***
Non-G7	0.1	0.59***	0.9***
Sample 1 and Sample 2	0.15***	0.59***	0.93***
Sample 2	0.07	0.51***	1.37***
Sample 1 and Sample 2 – non G7	0.05	0.66***	1.04***

Source: Deloitte analysis

*Notes: Dependent variable: log domestic stock of knowledge; ***, **, * indicate rejection of the null at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS*

4.3 Objective 3: Assess the complementarity/substitutability between public and private R&D

This section explores the relationship between business funded R&D and government expenditure on research and innovation. The results of the analysis indicate that:

- Public investment on private R&D projects and university research stimulates business funded R&D suggesting complementarity between public and private R&D;
- The estimated impact of direct government R&D varies depending on the model specification and country sample considered but typically is statistically significant; and
- There is some evidence indicating that public R&D is more effective at stimulating private investment in non-G7 countries relative to G7 countries.

Business funded-government spending relationship (Sample 1)

Table 9 sets out the econometric estimates of the impact of government R&D expenditure on business funded R&D investment using Sample 1. Government investment is split into direct government, government-funded private and higher education investment. Four alternative model specifications are presented. Model 1 specifies private R&D as a function of government R&D whereas the remaining three models include additional regressors to control for confounding effects.

Table 9: Impact of government R&D expenditure on private R&D (Sample 1)

Variable type	Variable	Model 1	Model 2	Model 3	Model 4
Public R&D	Business R&D funded by government	0.17***	0.20***	0.13***	0.26***
	Direct government R&D	0.08	-0.07	0.20**	-0.18*
	Education R&D	0.87***	0.483***	0.72***	0.44***
Controls	GDP per capita		0.43***		0.34*
	Market capitalisation			0.002***	
	Trade openness				0.002
	% population in tertiary education				0.004

Source: Deloitte analysis

*Notes: Dependent variable: Business funded R&D; ***, **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS*

These results suggest that:

- **Government-funded business R&D.** Government-funded business R&D has a positive and statistically significant effect on business-funded R&D. The elasticity is relatively stable across model specifications indicating that a 1% increase in public-funded business investment is associated with a c. 0.2% increase in business-funded R&D.
- **Direct government R&D.** The results for direct government R&D are mixed. The elasticity is positive and insignificant when no control variables are included,

negative and insignificant when the impact of GDP is controlled for, and positive and significant when the market capitalisation is included in model. In Model 4, direct government expenditure has a negative and statistically significant effect indicating that 1% increase in direct government spending is associated with a 0.18% reduction in private R&D. This estimate is consistent with the crowding-out hypothesis.

- **Higher Education R&D.** Investment in higher education has positive and statistically significant effect across all model specifications although its magnitude depends on the control variables included. Notwithstanding this, investment in education has the largest effect on private R&D relative to the other two public R&D variables. The lowest elasticity (Model 4) suggests that a 1% increase in higher education expenditure leads to 0.44% increase in private investment.

Sensitivity analysis

Table 10 reports a number of additional estimates across alternative model specifications, estimation methods and sample periods. All models include the three government R&D variables, and GDP per capita as a control variable. The results suggest the following:

- **Government-funded business R&D.** Government-funded business R&D is again relatively stable across alternative models with an elasticity of around 0.2. The only exception is when a trend is included or the model is estimated by the pooled mean group (PMG) estimator, which provides counter-intuitive results (for example, the elasticity of direct government is unrealistically high).

- **Direct government R&D.** The results of direct government investment are mixed as before although its impact is found to be statistically insignificant in the majority of the cases.

- **Higher education R&D**. Higher education R&D is always positive and significant except in the PMG case.

Table 10: Sensitivity analysis (Sample 1)

Model/specification	Description	Business R&D funded by government	Direct government R&D	Education R&D	GDP per Capita
Trend	Country specific time trend	0.076**	-0.064	-0.105	0.836***
Estimator	FMOLS	0.238***	-0.132**	0.458***	0.472***
	PMG	0.652***	4.606***	0.152	-0.235
Sample period	1981 to 2007	0.178***	-0.063	0.45***	0.522***
	1990 to 2013	0.166***	0.009	0.416***	0.436***
Lag/lead specification	2 lags and 2 leads	0.098	0.181	0.993***	-0.015
	2 lags and 1 lead	0.17***	-0.009	0.879***	0.063
	1 lag and 2 leads	0.154***	0.03	0.948***	0.004
	1 lag and 1 lead	0.204***	-0.016	0.734***	0.201

Source: Deloitte analysis

*Notes: Dependent variable: Business funded R&D; ***, **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS with the exception of the FMOLS and PMG results*

Country sample analysis

Table 11 sets out the results using a number of alternative country samples.

- **Government-funded business R&D.** The elasticity of government-funded business R&D remains close to 0.2 across all samples with the exception of G7 countries for which the effect is statistically insignificant.
- **Direct government R&D.** The impact of direct government R&D is positive and statistically significant in the majority of cases with the exception of Sample 1 non-G7 countries.
- **Higher education R&D**. The impact of higher education R&D is positive and significant. The results also suggest that university R&D stimulates private R&D more in the non-G7 countries relative to G7.

Table 11: Impact of government R&D expenditure on private R&D (Sample 1 & Sample 2)

Sample	Business R&D funded by government	Direct government R&D	Education R&D	GDP per Capita
Sample 1	0.202***	-0.069	0.483***	0.433***
G7	-0.036	0.343**	0.296**	0.453***
Non-G7	0.231***	-0.144*	0.551***	0.362**
Sample 1 and Sample 2	0.209***	0.215***	0.652***	0.223**
Sample 2	0.232***	0.411***	0.595***	0.288
Sample 1 and Sample 2 - non-G7	0.227***	0.204***	0.699***	0.138

Source: Deloitte analysis

*Notes: Dependent variable: Business funded R&D; ***, **, * indicate statistical significance at 1%, 5% and 10%, respectively; Coefficient estimates are obtained by DOLS*

4.4 Summary: Preferred models

The report provides a large number of estimates using alternative model specifications and assumptions. These estimates are occasionally sensitive to the modelling strategy adopted. This section provides some guidance around the preferred model estimates and the estimates that could be used to inform the parameters of QUEST III.

Objective 1: Update the parameters in the knowledge production function

It is proposed to use one of two alternative approaches to determine the "best" coefficient estimates.

- **Single model.** The baseline specification is based on the preferred proxy of innovation, BP specification and estimation method, full sample period and optimal lag specification and therefore could be considered as the preferred model.
- **Multi-model averaging.** An alternative approach would be to combine the estimates from several models given the inherit model uncertainty, i.e. it is difficult to determine the extent to which one model is significantly better than other models. The average of all estimates reported in Table 4 (excluding those with counter intuitive estimates, i.e. *Worldwide patents and Trademarks models*) is 0.60 and 0.80 for R&D employment and international stock of knowledge, respectively. These estimates are close to the baseline estimates (0.64 and 0.81).

Table 5 provides additional estimates of the knowledge production function using alternative country samples. These estimates could be used to allow the parameters of the knowledge production function within QUEST III to differ across countries. Similar to the approach described above, the "best" estimates could be considered either the baseline model estimates or the average estimates from all alternative models presented in Table 5. The latter are set out in Table 12.

Table 12: Average of the coefficient estimates presented in Table 5

	R&D	International Stock of Knowledge
G7	0.25	0.86
Sample 1 - Non-G7	0.83	0.64
Sample 1 and Sample 2	1.01	0.74
Sample 2	0.74	1.43
Sample 1 and Sample 2 - non-G7	0.96	0.86

Source: Deloitte analysis

Objective 2: Differentiate between public and private R&D within the knowledge production function

The models presented in Table 7 use two alternative proxies for public R&D, number of public R&D workers and number of publications. The results suggest that public R&D employment has statistically insignificant effects on innovation whereas publications have statistically significant impact. The magnitude of the publications coefficient is similar to the magnitude of private R&D coefficient. The results presented in Table 8 are based on the same models but different country samples. The coefficient of public R&D varies significantly across samples which is likely to be explained by the high correlation of the explanatory variables. Due to this collinearity, it is difficult to rely on these estimates and it is recommended to use the approach discussed in the Task 3 report to differentiate between private and public R&D within the knowledge production function.

Objective 3: Assess the complementarity/substitutability between public and private R&D

On the basis of parsimony, the preferred model in the business R&D analysis is Model 2. Alternatively, an average of different models could be used to inform the parameters of QUEST III. For example, the average impact of business R&D investment funded by the government presented in Table 9 is 0.19 and the average coefficient of education R&D is 0.63. The impact of direct government R&D is statistically insignificant in the three out of four specifications and could be assumed that it does not have a material impact on business R&D.

5 Appendix

A Alternative innovation proxies

This section describes and evaluates the patent count measures considered in the analysis. Six alternative measures have been considered.

- **EPO:** measures patent applications to the European Patent Office. A patent granted by the EPO gives the applicant protection of his invention in all EPO member countries, although the patent must be validated at the national patent offices of the designated states.

- **PCT:** measures patent applications filed under the Patent Cooperation Treaty. Under the PCT, inventors can file a single international application to a single patent office and then enter the national stage in other designated countries at a later stage, but within 30 months.

- **USPTO:** measures the number of patent applications to the United States Patent Office. This measure was previously used by Bottazzi and Peri (2007) as well as Bottasso et al. (2015).

- **Triadic:** measures the sets of patents that have been applied for at the EPO, the Japan Patent Office (JPO) and the USPTO.

- **Worldwide:** is a relatively new measure set forth by de Rassenfosse et al. (2013) that attempts to measure the total count of priority applications filed by a country's inventors regardless of the patent office.

In addition, trademarks have been used an alternative measure of innovation where trademarks measures trademark applications filed directly with national intellectual property offices as well as under the Madrid System.[37] While trademarks are common across a variety of industries, the main disadvantage of this measure is that not all trademarks represent new products or innovation.

The various patent measures have been assessed qualitatively and quantitatively. Drawn from the insights of de Rassenfosse et al. (2013), the main qualitative points of comparison are:

- **Geographic bias** refers to systematic bias in the number of patent applications due to proximity of countries to the country of the patent office. For example, countries closer to the US may be more likely to file USPTO patent applications;

- **Time effects** indicate variation in propensity to patent over time; and

- **Value** indicates the average economic value of patents measured by each indicator.

[37] The Madrid System allows individuals to file one application to protect their trademark in the 97 members of the Madrid Union.

Figure 10: Comparison of innovation proxies

Measure	Geographic Bias	Time Effects	Value	Quantitative assessment
EPO	Medium	Yes	Medium to high	- Relatively stable across the majority of the countries - Strong cross-sectional and time-series correlation with alternative patent measures
PCT	Low	Yes	Varying	- Surge in patent filings in the late 80s and early 90s witnessed across countries
USPTO	Strong	No	Varying	- Structural break in 2000 due to change in patent disclosure rules
Triadic	Low	Yes	High	- Shorter time series available than the other measures (1985 - 2011) - Change in USPTO patent disclosure have also affect triadic patent fillings
Worldwide	None	No	Varying	- Volatile and relatively low correlation with alternative innovation proxies

The comparison suggests that the EPO patent measure exhibits the best qualities for the purpose of this analysis. While the PCT measure also appears to hold good qualitative properties, high growth across countries may suggest a larger role of propensity to patent for this series. Nevertheless, patent applications filed under the PCT, the worldwide patent measure, and trademarks applications have been used as alternative measures as part of the sensitivity analysis.

B Sensitivity of results to stock of knowledge parameters

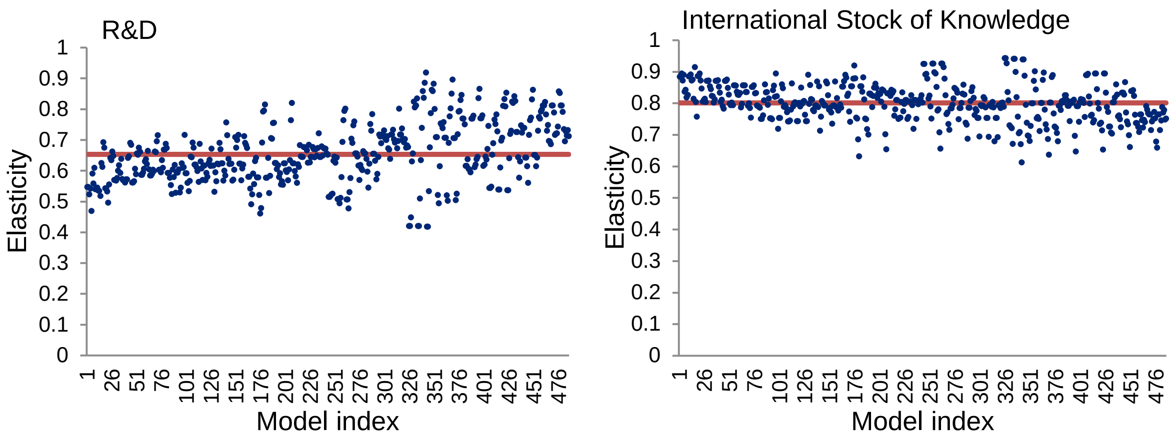
The sensitivity of the baseline estimates to the stock of knowledge parameters was checked across a wide array of parameter specifications for Objective 1. In addition to the parameters described in Figure 3, the start year of estimation plays an important role as it determines the length of time from the initial year (t_0) for which the stock has been allowed to accumulate. A larger window of time after the initial year may reduce the effect of any imprecision in the calculation of the initial stock at t_0 but also leads to a decreased sample of time used in estimation.

To check the sensitivity of the results, different combinations from the following set of parameters were used to construct the domestic stocks of knowledge:

- The initial year, t_0, with values from 1976 and 1984;
- The stock depreciation rate, δ, was set at 8%, 10%, as well 12%;
- The number of years used in the calculation of the growth rates, τ, with values of 5, 10 or 15; and
- The start year of estimation was set at 1985 or 1990.

The figure below illustrates the estimated long-run DOLS elasticities across the range of parameters. Across the different parameter specifications the results fall within the range of the elasticities reported in Section 0. Long-run elasticity estimates for the international stock of knowledge are particularly stable with an average of 0.8 and a standard deviation of 0.06. The mean estimated elasticity of R&D is 0.65 with a standard deviation of 0.09.

Figure 11: Sensitivity analysis (stock of knowledge parameters)



Source: Deloitte analysis

C Correlation matrices

This section sets out the correlation matrices of the variables used in each of the objectives.

Table 13: Correlation matrix for Objective 1 variables (Sample 1)

	Domestic Stock of Knowledge	Researchers	Total R&D Personnel	Total R&D Expenditure	Exports	GDP per capita	Fees
Domestic Stock of Knowledge	1.00						
Researchers	0.90	1.00					
Total R&D Personnel	0.91	0.95	1.00				
Total R&D Expenditure	0.95	0.96	0.94	1.00			
Exports	0.93	0.90	0.86	0.93	1.00		
GDP per capita	0.94	0.91	0.85	0.95	0.96	1.00	
Fees	-0.61	-0.57	-0.54	-0.61	-0.67	-0.63	1.00

Source: Deloitte analysis

Notes: Pooled time demeaned correlation

Table 14: Correlation matrix for Objective 2 variables (Sample 1)

	Domestic Stock of Knowledge	Researchers	Total R&D Personnel	Total R&D Expenditure	Public Researchers	Private Researchers	Publications
Domestic Stock of Knowledge	1.00						
Researchers	0.91	1.00					
Total R&D Personnel	0.92	0.95	1.00				
Total R&D Expenditure	0.96	0.96	0.95	1.00			
Public Researchers	0.81	0.92	0.86	0.87	1.00		
Private Researchers	0.89	0.96	0.93	0.94	0.79	1.00	
Publications	0.93	0.87	0.89	0.91	0.80	0.84	1.00

Source: Deloitte analysis

Notes: Pooled time demeaned correlation

Table 15: Correlation matrix for Objective 3 variables (Sample 1)

	Business R&D funded by business	Business R&D funded by government	Direct government R&D	Education R&D	GDP per capita	Market capitalisation	Trade openness	% population in tertiary education
Business R&D funded by business	1.00							
Business R&D funded by government	0.53	1.00						
Direct government R&D	0.60	0.64	1.00					
Education R&D	0.90	0.44	0.58	1.00				
GDP per capita	0.89	0.34	0.60	0.94	1.00			
Market capitalisation	0.55	0.15	0.20	0.52	0.53	1.00		
Trade openness	0.65	0.32	0.34	0.65	0.65	0.37	1.00	
% population in tertiary education	0.83	0.37	0.55	0.85	0.89	0.50	0.58	1.00

Source: Deloitte analysis

Notes: Pooled time demeaned correlation

D Unit root test results

Table 16 to Source: *Deloitte analysis*

*Notes: Im Pesaran and Shin panel unit root test results; Null hypothesis: series contain a unit root; *** , **, * indicate rejection of the null at 1%, 5% and 10%, respectively*

Table 18 report the unit root tests for the variables used in the analysis. The tests suggest that the levels of R&D measures are non-stationary whereas the first difference is stationary, i.e. R&D is integrated of order one. The results for the stock of knowledge are less clear-cut. For instance, some of the tests indicate that the level of stock of knowledge is stationary.

Table 16: Panel unit root test results for Objective 1

Transformation	Variable	Sample 1	Sample 1 and Sample 2	Sample 2	1990-2011
Level	Domestic stock of knowledge	-1.31*	-2.54***	-2.32**	-1
	R&D	0.75	1.46	1.32	0.77
First difference	Domestic stock of knowledge	-1.01	-3.15***	-3.52***	-1.6*
	R&D	-13.51***	-16.94***	-10.43***	-11.43***

Source: Deloitte analysis

*Notes: Im Pesaran and Shin panel unit root test results; Null hypothesis: series contain a unit root; *** , **, * indicate rejection of the null at 1%, 5% and 10%, respectively*

Table 17: Panel unit root test results for Objective 2

Transformation	Variable	Sample 1	Sample 1 and Sample 2	Sample 2	1990-2011
Level	Private R&D	1.86	2.17	1.21	2.12
	Public R&D	0.57	0.79	0.55	-0.58
	Publications	-4.49***	-4.12***	-1.24	-0.59
First difference	Private R&D	-12.35***	-16.07***	-10.37***	-10.81***
	Public R&D	-11.67***	-15.25***	-9.88***	-9.79***
	Publications	-13.91***	-17.89***	-11.33***	-9.23***

Source: Deloitte analysis

*Notes: Im Pesaran and Shin panel unit root test results; Null hypothesis: series contain a unit root; *** , **, * indicate rejection of the null at 1%, 5% and 10%, respectively*

Table 18: Panel unit root test results for Objective 3

Transformation	Variable	Sample 1	Sample 1 and Sample 2	Sample 2	1990-2014
Level	Business R&D funded by business	-0.63	1.25	2.59	1.53
	Business R&D funded by government	-1.21	-1.63*	-1.09	-1.58*
	Direct government R&D	-0.24	1.08	1.9	1
	Education R&D	0.71	0.94	0.61	0.97
First difference	Business R&D funded by business	-9.5***	-13.87***	-10.17***	-9.13***
	Business R&D funded by government	-16.67***	-21.12***	-13.05***	-15.32***

	Direct government R&D	-12.88***	-16.67***	-10.6***	-12.75***
	Education R&D	-13.55***	-18.23***	-12.2***	-12.95***

Source: Deloitte analysis

*Notes: Im Pesaran and Shin panel unit root test results; Null hypothesis: series contain a unit root; *** , **, * indicate rejection of the null at 1%, 5% and 10%, respectively*

E Literature on impact of government R&D and policies on business R&D investment

This section provides a summary of the macro literature that looks at the impact of government efforts and policies associated with R&D on business-funded R&D investment. The literature review focuses on studies published in the last 20 years.

Paper	Policy instrument	Model specification	Estimation approach	Sample	Results/elasticities
Diamond (1999)	(1) Government expenditure on R&D, (2) Higher education R&D expenditure	Dependent variable: Business funded R&D Controls: GDP and personal income	OLS in first difference - short run effects only	US data from the 1960s to 1990s	Elasticity of federal spending on business expenditure ranges from 0.51 to 0.62
Varsalakis (2001)	Protection of intellectual property rights	Dependent variable: Total R&D Intensity: R&D expenditure to GDP Controls: GDP per capita, degree of openness of the domestic market, national culture index, monopolistic power of the innovator, and international spill-overs	Cross-sectional OLS	50 countries (year differs by country but typically obtained for a single year in the 1990s)	Patent protection elasticity is c. 0.5
Bloom and Griffith (2001)	Cost of R&D	Dependent variable: R&D expenditure performed by business Controls: GDP, Foreign user cost (weighted foreign tax credits), country and time dummies	Within-groups Instrumental Variable estimator	Australia, Canada, France, Germany, Italy, Japan, UK, and the US from 1979 to 1997	Short-run elasticity of R&D expenditure performed by business with respect to cost of R&D: -0.14 Long-run elasticity of R&D expenditure performed by business with respect to cost of R&D: -1.18[38]
Bloom, Griffith and Van Reenen (2002)	Cost of R&D	Dependent variable: R&D expenditure funded by manufacturing business Controls: GDP, country and time dummies	Within-groups Instrumental Variable estimator	Australia, Canada, France, Germany, Italy, Japan, Spain, UK, and the US from 1979 to 1997	Short-run elasticity of R&D expenditure performed by business with respect to cost of R&D: -0.1 Long-run elasticity of R&D expenditure performed by business with respect to cost of R&D: -1.[39]

[38] The main component of the cost of R&D is tax credits and hence the elasticities imply that a 1% increase in tax credits would lead to 0.14% and 1.13% increase in business R&D investment in the short- and long-run, respectively.
[39] These results could be interpreted in the same way as the results reported by Bloom and Griffith (2001): a 1% increase in tax credits would lead to 0.1% and 1% increase in business R&D investment in the short- and long-run, respectively.

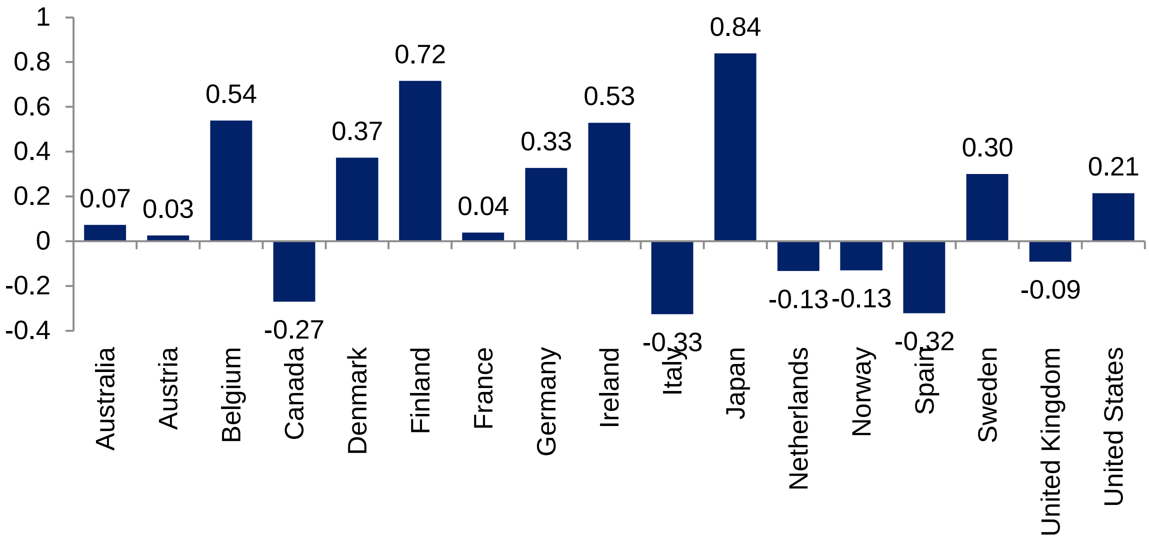
Kanwar and Evenson (2003)	Protection of intellectual property rights	Dependent variable: Total R&D expenditure as a percentage share of GNP Controls: Real Savings share of GDP, Real GDP per capita, Average number of schooling years in population over 15, Total literacy rate in population over 15, Black market exchange rate premium dummy, Political instability dummy, Real lending rate of interest	Random Effects (GLS)	31 developing and developed countries over 1981-1990 (total of 62 observations or two five-year averages for each country)	Ginarte and Park (1997) Intellectual property index: 0.47 - 1.13
Guellec and Pottelsberghe (2003)	(1) Government funding of business R&D, (2) R&D tax credits, (3) government expenditure on R&D, (4) Research performed by universities	Dependent variable: Business funded R&D Controls: GDP, country and time dummies	First difference autoregressive model	17 OECD countries from 1983 to1996	- Direct government funding and tax incentives has a positive effect on business financed R&D. However there are strong non-linear effects: 1. Direct government funding and R&D tax incentives are substitutes: increased intensity of one reduces the effect of the other 2. Direct funding as well as tax incentives are more effective when they are stable over time: firms do not invest in additional R&D if they are uncertain of the durability of the government support 3. The impact of government funding on business generated R&D is U-shaped: it increases up to a certain threshold and then decreases beyond - University research has no impact on business funded R&D - Government R&D performed in defence has a negative impact on business financed R&D. Other government R&D has no effect
Jaumotte and Pain (2005)	(1) Tax credits, (2) protection of intellectual property rights	Dependent variable: Business-funded R&D expenditure Controls: GDP, inflation, corporate profits as % of GDP, ratio of bank credit plus stock market capitalisation to GDP, stock market capitalisation,	Panel error correction model	20 OECD countries from 1982 to 2001	Long-run elasticities Tax credits: -0.8 to -1 Intellectual property rights: statistically insignificant effects

		corporate profits, profit share of GDP, indicator of product market regulation, indicator of employment protection legislation, indicator of strength of FDI restrictions, trade openness adjusted for population size, real exchange rate, ratio of imports			
Falk (2006)	(1) Government-funded business R&D, (2) R&D performed by higher education institutions as a percentage of GDP, (3) tax credits, (4) protection of intellectual property rights	Dependent variable: Business R&D intensity: share of business sector R&D expenditure to GDP Controls: high-tech export share, GDP per capita, average number of schooling years, share of university graduates, openness, investment ratio, private investment ratio	GMM and first-difference GMM	21 OECD countries from 1985 to 2002	Long-run elasticities Government funded R&D: 0-0.29 Higher education R&D: 0.24-1 Tax credits: -0.84 Intellectual property rights: 0.8
Westmore (2013)	(1) Government-funded business R&D, (2) tax credits	Dependent variable: Business-funded R&D expenditure Controls: GDP, inflation, indicator of product market regulation	Panel error correction model	19 OECD countries from 1982 to 2008	Long-run elasticities Government-funded business R&D: 0.18-0.56 Tax credits: -0.49 to -1.15
Wang (2013)	Protection of intellectual property rights	Dependent variable: Total R&D Intensity: R&D expenditure to GDP Controls: Output, openness, percentage of the population having tertiary education, number of researchers, population density, government-performed R&D, government budget imbalance, fixed capital formation, unemployment rate, inflation rate, interest rate, and the share of industrial production in GDP, country and time effects	Extreme Bounds Analysis	26 OECD countries from 1996 to 2006	Impact of intellectual property protection rights on R&D intensity is ambiguous

F Objective 3: Fixed effects

The table below reports the country fixed effects from Model 1 (Table 9) and reflect the impact of time invariant unobserved country effects on business funded R&D investment.

Table 19: Fixed effects from Model 1 of Table 9



Source: Deloitte analysis

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The Directorate General for Research and Innovation of the European Commission commissioned Deloitte and RAND Europe to undertake a study with the aim to better understand the impact of public policy on innovation. In particular, the objective of the study is twofold: enhance the evidence base around the impact of public policy on research and innovation; explore possible modifications in QUEST III to evaluate a number of innovation policies and reforms.

This report focuses on the update of the parameters of the knowledge production function in QUEST III using more up-to-date data and a broader set of countries. Furthermore, the current specification of the knowledge production function is extended by differentiating between public and private R&D.

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