Rates of return to investment in science and innovation

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Executive Summary

This report provides a comprehensive overview of the evidence relating to the rate of return to investment in science and innovation. Alongside a summary of the existing evidence, it includes some original econometric estimates and case studies designed to fill some of the gaps in the current literature.

Approaches to measuring the rate of return

The most common approach to measuring returns relies on the estimation of a **production function** which relates investment inputs (most often expenditure on R&D) to a measure of output or productivity. This gives a solid theoretical economic underpinning to the model, and such models can be readily estimated using survey data or aggregate time series data at the level of countries, industries or firms. Spillover benefits of investments can also be picked up through this approach. However the method has a number of disadvantages: there are significant econometric and definitional challenges, and these methods are agnostic about the *mechanisms* through which investments generate returns.

These mechanisms can be better explored using **case study** evidence, or through an emerging '**microeconomic**' approach which collects detailed data on research and researchers to analyse how knowledge is produced and how it disseminates to the private sector to help generate innovation. The microeconomic approach is still at an early stage of development, and may only be able to pick up measurable behaviours and so miss some ways in which knowledge investments help to generate economic returns.

The rate of return

Drawing on production function methods, the existing literature tends to estimate **private rates of return to R&D investments of around 30% (mean) or 20 to 25% (median)**. There is no clear evidence that these average private returns differ according to the unit of analysis used to estimate the model (e.g. firm-, industry- or country-level data).

Social returns, based on spillover benefits from R&D conducted by one agent to the productivity or output of other agents, **are typically 2 to 3 times larger than private returns.**

Investments in 'science and innovation' are not just limited to scientific research and development (R&D), but rather comprise a range of 'intangible investments' which help to drive innovation. The evidence on private and social rates of return to non-R&D intangible investments is rather thin and shows mixed results so far. This appears to be a particularly important area for further research and data collection, particularly given evidence that non-R&D intangibles are much larger in magnitude than traditional scientific R&D in the private sector. Our case study findings also suggest that companies themselves perceive their innovation investments to go beyond scientific R&D, even in sectors like aerospace and life sciences where traditional scientific R&D remains hugely important.

There is mixed empirical evidence on whether the private returns to product or process innovation are higher; the contradictory findings may relate to different methodological approaches and measurement difficulties. Nevertheless it seems clear that both forms of innovation are important to industry. The firms we spoke in the aerospace and life sciences sector as part of this study all defined innovation more broadly than introducing new products. In particular, all firms had been innovating in the way they innovated, including how they engaged with external collaborators. Interestingly, the models being adopted even across firms within an industry were quite different, suggesting there is not necessarily any single 'optimal' model of collaboration to drive innovation.

Rate of return to public funding of R&D

Studies which look at the social returns to publicly-funded R&D investments have found some significant, positive returns (around 30 to 40%) based on the agricultural sector. More recent evidence, looking at how different industrial sectors interact with publicly-funded R&D, has **estimated positive and significant social returns of around 20% for UK public R&D investments**. However, this is evidence is based on modelling the impact of public R&D on private sector productivity. This is likely to *understate* the economic return to public R&D spending. Public R&D tends to be more basic than applied, more risky, and may only be commercialised through additional private investments to absorb the knowledge making it hard to attribute the returns adequately. In addition, the benefits of public R&D may be felt in other ways, including their impact on national health, education, security and the productivity of the public sector. These are difficult to capture in an econometric framework.

Studies which have looked at whether the returns to publicly-funded R&D conducted by industry differ from those funded privately have often found negligible benefits of the publicly-funded investments. This could simply reflect the fact that publicly-funded R&D conducted by industry tends to be different in nature than privately-funded R&D (perhaps somewhat less specific in nature or further from market).

Impact of different channels for public R&D funding

There is **some evidence that**, at least in terms of their impact on private sector productivity, **public R&D channelled through the research councils leads to higher social returns than R&D conducted by government departments** (civil and defence) **or channelled through higher education**. This may be because research councils conduct and fund R&D that is 'closer' to industry. We also find evidence that within research council investments, the highest social returns come from science-based and applied research. Again, these may be closest to the sorts of R&D investments made by the private sector.

These findings do not suggest that the public sector should only fund this kind of R&D; rather, that the social returns to other publicly-funded R&D either accrue with long lags which we cannot pick up, or through other mechanisms than their impact on the private sector. Further evidence on these issues would be very useful.

There are also clear interdependencies between different forms of public R&D investments – for example, research council funds that go towards academic institutions. This makes it difficult to disentangle the returns by source of funds.

Links to academia, and to types of facilities

Our case study evidence suggests that **links to academia are increasingly seen as an important complement to the in-house knowledge of industry** in strategic sectors of the UK economy. Being able to draw on academic skills and new ideas is critical to longer-term innovation, though companies in both aerospace and life sciences expressed concern about fragmentation of academic knowledge rather than the creation of 'centres of excellence', which could make it harder to spot potentially commercial opportunities.

In aerospace, the value of large-scale capital facilities (such as catapult centres) was seen, in part, to help provide these central hubs for knowledge-sharing and dissemination. The facilities themselves also allow industry to test new ideas at scale and jointly contribute to costly capital equipment which would be uneconomic for a single firm. Thus **both capital and current investments in R&D by the public sector were thought to be important in generating innovation**, again suggesting it is hard to disentangle rates of return.

More widely, survey evidence has found that a significant amount of private sector output and innovation is thought to depend critically on public funding of academic research. In our case study sectors, engagement with academia and the underpinning basic science base is also seen to be a key driver of where firms locate private R&D investments.

There is a considerable literature which suggests that links between academic researchers and business can be useful in the innovation process. Not much of the literature is able to quantify the impact of such engagement on the returns to knowledge investments, though geographic proximity between academics and industry does appear to affect returns. Spillover benefits from university research are felt most heavily by firms located near to the institution, and many firms appear to co-locate near to high-quality academic research facilities. This was also seen to be important in the firms we spoke to.

Relationship between public and private investments

In principle, there is a risk that publicly-funded R&D may crowd out privately funded R&D, either through a straightforward displacement effect or through the impact on the labour market for scientists and researchers. However, **most of the empirical evidence seems to suggest that public R&D incentives *crowd in* additional private R&D**. This evidence is strongest in terms of fiscal incentives or public subsidies for private R&D; the evidence in terms of R&D conducted by the public sector is more mixed but so far rather thin.

The timing of returns to R&D investment

Lag times between **private R&D investments and commercialisation yielding economic returns tend to be relatively short, ranging from around 1 to 3 years.** Studies looking at the lags between **public R&D and commercial returns find much longer lags**. This may reflect a larger share of public R&D investments going towards basic research without specific commercial application in mind.

Private investments can also have very long lags before returns are generated. In key R&D-intensive industries like aerospace and life sciences, lags in the process of developing new technologies are typically much longer, outcomes are uncertain and development costs are high. Public support for the development process across the whole gestation lifecycle from academic generation of new knowledge through to market is therefore seen to be very important, rather than being necessary only at one point in that process.

A number of studies have suggested that **private R&D investments depreciate at a rate of around 20% per year**, consistent with product lifecycles in the order of 10 years before obsolescence. **Public investments are usually assumed to depreciate at much slower rates, if at all**. Of course, to the extent that innovations build upon each other, the 'value' of an innovation may remain even if the economic returns to a particular new product decline.

There is a lack of clear evidence on whether depreciation rates are constant or change over time; much of this is due to uncertainty about the expected lifecycle of a new innovation. For example, in aerospace, whilst new aircraft are expected to last for decades, the design of individual components can change quite quickly in the face of new knowledge; this can generate uncertainty about the profile of returns for suppliers of components and parts. In life sciences, patents give some certainty over returns for a time, though the actual returns will depend on continued demand for any new products and the extent to which generic drugs can be introduced once the patent expires.

1 Introduction

1.1 Background

Frontier Economics were commissioned by the Department for Business, Innovation and Skills (BIS) to provide evidence on the rates of return to investments in science and innovation. In particular, there was interest in understanding better:

- What the current evidence base suggested the marginal private and social rate of return was to investments in research and development (R&D) or other forms of 'knowledge' investments, and the ways in which social returns exceed private returns;
- How these returns vary across different kinds of investment (such as those in large capital facilities compared with investment in salaries and other 'current' knowledge spending);
- Any evidence on the wider influences on these returns, how long knowledge investments take to yield economic returns, and the duration and profile of those returns over time.

To address these questions, we used three approaches:

1. A thorough **review and synthesis of the existing literature** (relying on a combination of academic economic literature, government publications and the grey literature);
2. Original **econometric work** looking at the social returns to different forms of publicly-funded R&D investments;
3. **Case studies** with four firms across two key strategic industries (life sciences and aerospace) to understand better the role and importance of publicly-funded knowledge investments in driving innovation in those industries.

The report is organised as follows. We first set out (Section 1.2) a clear economic framework to guide the analysis. This addresses a number of key issues, such as what we understand 'science and innovation' or 'knowledge' investments to mean, the pathways linking these investments to innovation outcomes which yield economic returns, and the methods used in the current literature to estimate rates of return to these investments. We then describe the results from our literature review (Section 2) in detail, including an assessment of some of the key gaps in terms of the issues raised by the economic framework. The results of our econometric analysis, which help fill in one particular gap around the returns to different forms of public R&D investments, are set out in Section 3, before the analysis and evidence from the case studies is described in Section 4. Section 5 concludes by setting out some opportunities for further analysis.

1.2 Economic framework

Economic theory has long stressed that innovations generating technical progress are key drivers of sustained improvements in living standards. As emphasised by the work of Romer, among others, investment in 'knowledge' is a key input affecting the rate of technical progress. Knowledge investments help to generate new products, processes and ideas which can be used to create new goods and services or to produce existing goods and services more efficiently.

These innovations lead to private returns in the form of increased profit and economic activity. Innovations can also be used by other firms to increase their own profit, generating positive externalities and wider, social returns from investments as well. Some knowledge investments may also be beneficial to wider society without having direct benefits for the private sector, having the flavour of 'public goods' which individual firms may not be willing to pay for.[1] This can include investments which improve national health, skills, defence and security, or which improve the efficiency of the public sector.

The presence of social returns to knowledge investments both through positive externalities and public goods generates an economic rationale for public support for such investments, as otherwise (from a social perspective) there would be too little investment. Intervention can include financial and non-financial incentives for private investment as well as direct public investment in R&D. Public funding makes up a large share of UK R&D expenditure: Haskel et al. (2014) suggest that just under one-third of UK R&D spend was publicly funded in 2011 (£8.65 billion of £27.38 billion total).[2]

1.2.1 What is meant by investments in science and innovation?

Much of the literature focuses on research and development (R&D) investments by the public or private sector, using data on past and current investments to try and construct a measure of the 'stock' of knowledge in the economy or the 'flow' of new knowledge investments. However as pointed out by Goodridge et al. (2012), among others, scientific R&D is only one of a set of wider 'intangible investments' in knowledge which help to drive innovation and generate economic returns. Corrado et al. (2005) develop a framework classifying intangible investments into three categories:

- **Computerised information** – including computer software and databases developed for a specific businesses' use;

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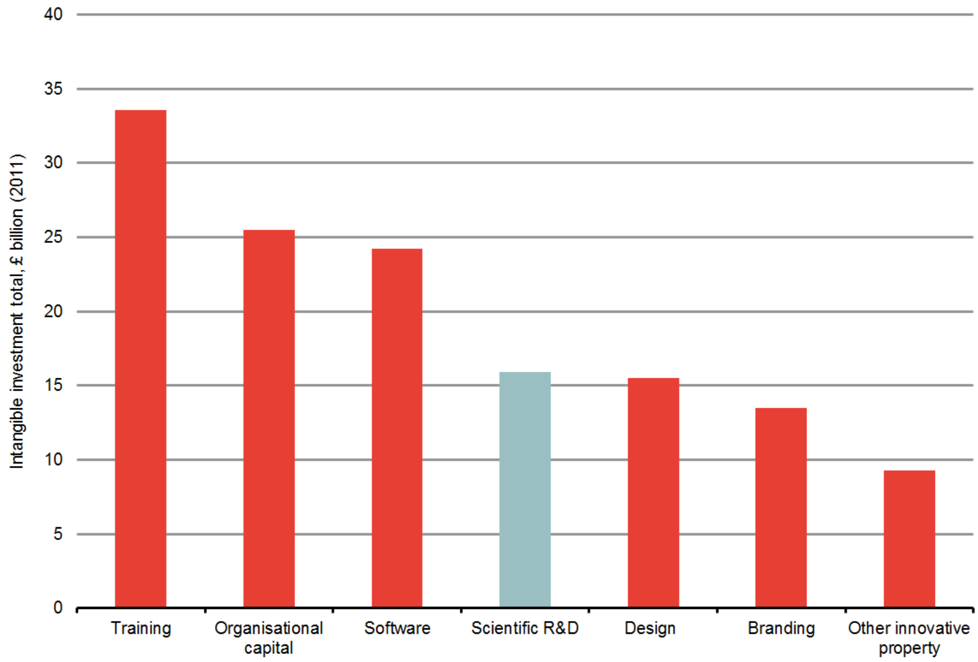
[1] Public goods are **non-rival** and **non-excludable**. Non-rivalry means that use of the good by one person does not reduce the amount available for someone else to use – in the case of knowledge, for example, one firm can download and read a published research paper and this does not preclude another from doing so. Non-excludability means that the good is available to everyone. Knowledge in some forms may be partly excludable (papers may be behind paywalls, new processes or products can be granted temporary monopolies in the form of patents or copyrights and so on) which gives private firms an incentive to invest as they are allowed to appropriate the returns for at least some time period. We return to these issues in a discussion of the social returns to investment in science and innovation below.

[2] See Exhibit 23 of Haskel et al. (2014). Publicly-funded R&D is the sum of government, research councils, Higher Education Funding Council and higher education (rows 1 to 4).

- **Innovative property** – including scientific R&D, exploration of minerals, costs of licensing and copyright, product design and development;
- **Economic competencies** – including firm-specific human capital (training costs), market research and brand development, and investments in organisational capital and structure.

Figure 1. Estimated intangible investments by UK market sector firms, 2011



Source: Goodridge et al. (2014), Table 1. Note: "Software" and "Design" each includes own-account and purchased categories. "Other innovative property" comprises non-scientific R&D, financial product innovation, artistic originals and mineral exploration.

There is evidence that private sector spending on non-R&D intangible investments is considerably larger than R&D spending (see **Figure 1**).[3] Of total intangible investments of £137.5 billion by UK market sector firms in 2011, Goodridge et al. (2014) estimate that only £15.9 billion (just over 11.5%) went on scientific R&D. Spending on training, organisational capital and software were all larger than R&D spending.

Do all intangible investments drive innovation forward? Spending on branding (advertising and market research) may be more about business-stealing than market expansion through innovation. However it is not clear that we can simply

[3] Details of the methods used to calculate the figures and datasets can be obtained from http://www.nesta.org.uk/publications/uk-investment-intangible-assets.

divide each class of intangible investments into 'innovative' investments or otherwise: for example, firms undertake market research in part to understand which new products would be most desired by consumers, and advertising is part of the process by which innovations can diffuse through the economy.

1.2.2 Private and social returns

Conceptually, returns on science and innovation investments can accrue *privately* to those making the investments, or *socially* to others. Social returns encompass both increases in profits for firms who can make use of the innovations created by other firms or in the public sector, as well as harder-to-measure returns to wider society such as gains to health, well-being, security and efficiency in the policy making process and the delivery of public services.

It is important to note that in thinking about 'private' and 'social' returns the level of analysis is important. To estimate rates of return, most of the existing econometric literature uses data on output (value-added or productivity) and knowledge investments at the firm-, industry- or national-level. These estimates yield private returns to firms, industries or countries from their own investments. Social returns can be captured by including measures of the investments made by other firms, industries or countries in the model. Again, though, the social returns are specific to the study: when using firm-level data, the social return is based on investments by other firms (usually in the same sector). In this case, the 'social return' using firm-level data is akin to a 'private return' using industry-level data. Similarly, social returns to an industry depend on investments made in other industries, and are akin to private returns at a national level. Social returns when using data at a national level reflect global knowledge spillovers.

1.2.3 What are the key "rates of return" of interest?

If we wanted to understand the return to the UK economy of a £1 investment in knowledge, the key measure would be national-level, social rates of return to intangible investments. This social return should encompass spillover benefits in the private sector, and any wider public benefits of the investment.

As described in Section 2, the literature does not provide much evidence of this particular measure, but instead looks at narrower definitions of investment (R&D rather than wider intangibles) or returns (firm- or industry-level private and social returns, with little evidence on the value of 'public good' investments).

Figure 2 sets out a taxonomy of the levels of analysis and what the returns mean in each case.

Figure 2. Types of returns to investment

Type of investment	Unit of analysis		
	Firm-level	Industry-level	National-level
R&D investments ("science")	Private returns to firms' R&D spending	Private returns to industry R&D spending Social returns to firms' R&D spending	Private returns to national R&D spending Social returns to industry R&D spending Wider public good benefits from R&D spending
Total intangible investments ("science & innovation")	Private returns to firms' intangible spending	Private returns to industry intangible spending Social returns to firms' intangible spending	Private returns to national intangible spending Social returns to industry intangible spending Wider public good benefits from intangible spending

Source: Frontier Economics

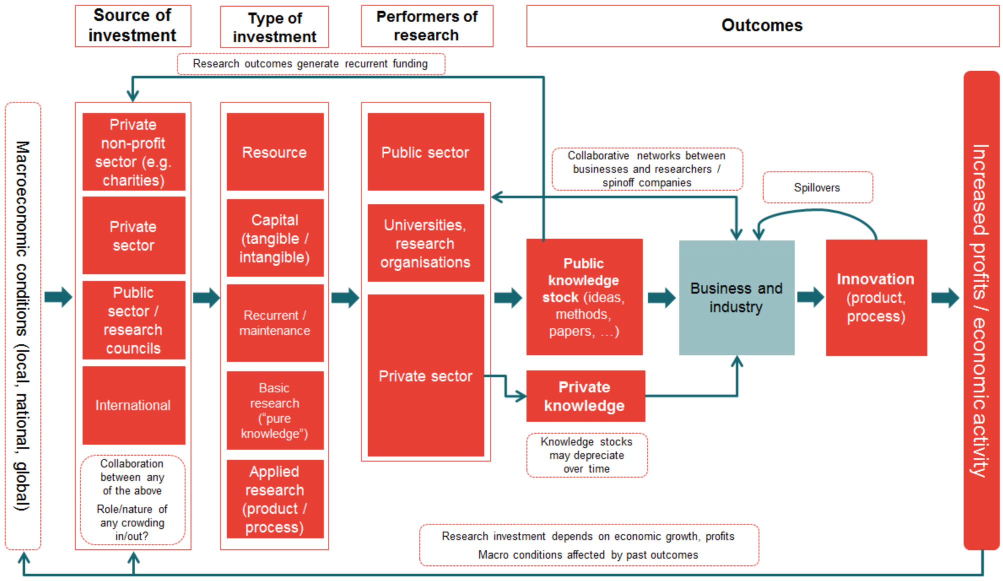
1.2.4 Wider issues of interest

At a high level, as just described, we are interested in understanding the economic returns to knowledge investments. However, the pathways linking these investments to innovation and economic returns are complex, including feedbacks and spillover effects, external influences, and a number of types, performers and sources of investment (see **Figure 3** for a stylised illustration).

As well as evidence on the returns, we therefore consider some other key issues which might be expected to influence the returns to particular investments:

- Does the **source** of investment (private or public) matter for the returns, and why? Is there any variation in the returns for different kinds of public or private knowledge investment?
- Is there variation in the returns by the **type** of investment, such as capital or current investment, investment in products or processes?
- Are different types of investment **substitutes or complements** for one another – for example, does public investment in knowledge crowd in or crowd out private investment?
- What is the **lag time** between investment and innovative outcomes? How long are the benefits from innovation expected to last?
- How important are **links and networks** in increasing the returns to knowledge investments, for example through generating spillover effects or helping publicly-funded knowledge be absorbed by the private sector?
- Are there important **external factors** which affect the returns?

Figure 3. Framework linking science and innovation investment to economic returns



Source: Frontier Economics

1.3 How are rates of return estimated?

In empirical analysis of the rates of return to knowledge investments, the economics literature has developed two main broad methodologies:[4]

- a **'macroeconomic'** approach which attempts to measure returns directly by estimating a production function linking inputs (including measures of knowledge) to outputs such as economic activity or productivity; and
- a **'microeconomic'** approach which attempts to look directly at the pathways linking inputs and outputs and provide ways to measure the importance of different channels between them.

The microeconomic approach is still fairly embryonic relative to the well-established macroeconomic/production function approach.

1.3.1 Production function ('macroeconomic') approach

We set out the details of this approach, including how the econometric methods are derived and further discussion of the key modelling issues, in Appendix A.

[4] Other methods to quantify returns are also used; we describe some findings from other methods in Section 2.2.2.

The broad framework of the production function methodology dates back to Griliches (1979). The method relates a measure of output to measures of inputs, where "knowledge" is one of the input variables. The approach can be applied to data at the firm-, industry- or national-level, and is amenable to analysis using time-series, cross-sectional or panel data methods.

A number of different approaches to estimating production functions are used. Depending on the precise approach and assumptions made, the method yields estimates of the *elasticity* of output with respect to knowledge capital, or the *rate of return* to knowledge investments. Sometimes, a two-stage approach is used, first modelling the relationship between knowledge investment and innovation, and second the relationship between innovation and output.

Regardless of the precise methods used, there are a significant number of econometric and measurement issues which have to be confronted when using a production function method. These are detailed in Appendix A, but include:

- Defining **output and knowledge investments** appropriately and dealing with key economic assumptions which underlie particular choices;
- The **functional form** of any underlying economic model from which the production function is derived, trading off modelling tractability with the desirability/realism of the economic properties;
- Econometric challenges such as **omitted variable bias**, the likely **endogeneity** or **measurement error** associated with the knowledge investment variable, **multicollinearity** of different inputs and **sample selection** issues.

Some of the key implications of these issues are:

- Measurement difficulties often lead to estimates based on manufacturing firms, where output and inputs are more straightforwardly defined, though this means the results are not necessarily transferable to other contexts (e.g. the returns to public investment in basic medical research).
- There is value where possible in using panel data for the analysis (whether the individual units of observations are at a country, industry or firm level in each time period), since this allows for unobservable fixed and time-specific differences across units of analysis to be controlled for and may help to deal with endogeneity problems under various assumptions about the form of the error term in the model.
- In general, lagged knowledge should be included in the model to allow for the fact it can take time for knowledge to lead to innovations which generate increases in output or productivity. This would suggest a need for some time series variation in the data. However it is not clear what the appropriate number of lags to include is, and with a short time series

it may not pick up the full effect (particularly if there are long lags to some forms of investment such as basic research).

Advantages of method

The production function method is somewhat of a 'black box', taking input and output data and correlating the two in more or less sophisticated ways. To the extent that we can be confident that the estimated return to knowledge investment is econometrically robust in the face of the problems highlighted above, this approach has a key advantage that in principle it is able to pick up the returns however they are realised. It therefore allows us to estimate the 'full' effect of the investment (though as noted above there may still be difficulties when the effects work through other inputs, or where the returns are not easily measured or quantified).

More pragmatically, the production function method is useful because it can be applied using data which are typically quite readily available from national statistics, or firm-level surveys which are often carried out in advanced economies. The method is flexible in allowing additional information to be incorporated from a range of data sources, and whilst there are obvious challenges with the assumptions which need to be made to make the analysis tractable, the underlying framework is at least clearly grounded in economic theory and principles.

The method is also useful in that it does allow for quantification of the returns. Given sufficient variation in the data, it is possible to look at how the returns vary according to who carries out the investment (for example, in firm-level studies, it is possible to see whether returns vary by interacting knowledge stocks with firm characteristics such as size or location) or the type of investment.

The estimates can encompass not just the private returns but also estimates of the social returns. The latter can be estimated by including in the model some measure of knowledge produced by others to see whether it has any additional effect on output. This usually relies on some way of weighting together all the knowledge stocks of the individual firms, industries or countries being analysed into a single 'outside knowledge' measure.[5] The weighting can be based on observed intermediate input flows between firms or industries, trade flows between countries, or other measures of 'closeness' which could be specific to the particular analysis.

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[5] It is not be possible to include the knowledge stock of all other firms, countries or industries in the model since this would lead to the number of unknown variables exceeding the number of equations to be estimated. Thus a single 'outside knowledge' stock is usually estimated.

Disadvantages of method

Measurement and econometric difficulties may not be easily overcome, which can cast some doubt on the interpretation of the estimates derived.

Another key downside of the 'black box' nature of the approach is that it does not allow any straightforward characterisation of the pathways between inputs and outputs. An understanding of the linkages therefore requires alternative methods, normally a combination of case studies and analysis of microeconomic data on researchers and research outputs, which we now discuss.

1.3.2 Microeconomic approach

An emerging literature aims at diving into the 'black box' linking knowledge investments to economic outcomes, using detailed data tracing the impacts of the investment. The emergence of this way of studying the economic impact of the production of knowledge is linked to interest in two themes:

- the improvement of science metrics based on the collection of large amounts of high-quality data (see Lane (2010) for a review);
- better understanding of the channels or pathways through which knowledge produced in universities and research institutes reaches the business sector and has eventually an economic impact.[6]

These themes are in fact apparent in two major on-going initiatives that adopt a microeconomic approach: the STAR METRICS project in the US,[7] and the Industry and Academic Engagement projects at Imperial College, London.[8] More information about these initiatives is given in Appendix A.[9]

Advantages of method

Compared to a traditional production function approach, the microeconomic approach has the potential to allow much more to be said about the channels through which different types of research investment yield measurable innovation outcomes.

[6] Aside from the approaches detailed in this section, a relatively large literature explores business and academic linkages and their impact on innovation and other outcomes. We summarise the relevant evidence in Section 2.4.4.

[7] Science and Technology for America's Reinvestment – Measuring the Effect of Research on Innovation, Competitiveness, and Science (https://www.starmetrics.nih.gov/)

[8] http://www3.imperial.ac.uk/innovationstudies/researchthemes/ourprojects/tric; http://wwwf.imperial.ac.uk/blog/tric/

[9] We are grateful to Julia Lane (American Institutes for Research) and Markus Perkmann (Imperial College, London) for helpful discussions on STAR METRICS and the Industry Engagement Project.

The effort so far in this approach is focused on the university sector. Detailed administrative data on academic research inputs and outputs should, in time, allow for a fine level of granularity in analysing how the 'academic production function' best generates research outcomes and how engagement with industry is best supported. To the extent that this could be traced through into impacts on industry and business it could also allow for a more direct estimation of the wider returns to research investments.

Combining administrative data with survey data of the researchers involved could also help identify the wider barriers and influences on the returns to different forms of investment.

Disadvantages of method

Although the micro approach can help identify specific pathways through which publicly-funded investments generate returns, it may only be able to measure specific parts of the pathway which are relatively more easily quantified (outputs such as academic outputs, spinoffs, patents; research grant inputs and so on). Translating this into estimates of returns will also necessitate some assumptions about the 'downstream' economic value of different forms of research outputs.

Even if we can place reasonably robust values on the outcomes of the research process, it may still be very hard to apportion that value to the different kinds of investments (e.g. capital and current components of total grants), since it is likely that both were required to generate the outcomes. Further, some benefits will be hard to value at all (public health benefits, improvements to policy making and so on), though of course this is also the case for any other methods used to try and estimate the returns to investment.

Although in principle the datasets should allow for a detailed examination of different forms of research investments and how these are used by researchers to generate outcomes, the modelling challenges are also quite significant. For example, research funding is not randomly assigned to individual staff: it may be that more "productive" researchers are better at winning funding or particular kinds of funding, for example.

2 Literature Review

2.1 Introduction and review methodology

This review sets out evidence from the existing literature on the private and social returns to investment in science and innovation. Our focus is not just on the magnitude of returns estimated in the published literature. Guided by the economic framework set out above, we also examine:

- Evidence for how private and social returns vary along a number of dimensions, such as the type of investment; and
- Evidence around the wider issues linking knowledge investments and later returns, such as how they are influenced by collaboration between researchers and firms, or how long innovations take to be realised following investment being made.

To conduct the review, we began by identifying a number of papers in the academic economics literature which have reviewed the empirical evidence on the returns to knowledge investment (Salter and Martin, 2001; Hall et al., 2009; Hall, 2011; Hall and Mohnen, 2013). We classify the studies according to the level of analysis and type of knowledge investments considered, drawing on the structure outlined in **Figure 2**.

We then reviewed individual papers identified in these articles to ascertain whether they cast light on any of the wider issues of interest set out in Section 1.2.4. We began by sifting the titles and abstracts of papers identified; those that appeared relevant were subject to a more thorough sift of the introductions and conclusions, and the final selected papers reviewed in depth with key findings extracted to a common template. To identify papers beyond those in the review articles, we used a number of sources including JSTOR, EconLit and Google Scholar. We also picked up relevant grey literature and working papers using wider Google searches, and searched the publication profiles of academics active in this field.

Having reviewed the material, we engaged in a thematic analysis, grouping the evidence according to the issues being examined.

2.2 The high-level returns to investment

This section sets out high-level evidence on the rates of return to investments in science and innovation, drawing on the framework set out in **Figure 2**. The evidence in this section draws largely on the academic economics literature and studies which have estimated returns using the production function method. In particular, we draw on Hall et al. (2009) looking at the private and social returns to R&D investments, supplemented with some additional evidence from European Commission (2005) and a wider search of the literature, in particular looking at the returns to non-R&D intangible investments.[10]

We begin by assessing the private returns, those accruing to the firm, industry or country making the knowledge investments. We then look at evidence for the social returns which accrue through spillover effects to others. The literature explored here has not considered other ways in which social returns might exceed private returns (e.g. through 'public good' benefits); we present some evidence on these wider sources of social return to investment in Section 2.3.

We cautioned in Section 1.2.3 that the returns will in part be influenced by the unit of analysis: 'private returns' from industry-level data may be quite similar to 'social returns' using firm-level data. We therefore distinguish the unit of analysis in our assessment of the literature. Beyond this, it is of course worth being cautious in comparing point estimates of the rate of return provided by different studies. There is unlikely to be a single 'rate of return' to all R&D investments and so it may not be possible to translate evidence from one study into the predicted impact of future investments. The results are very sensitive to the dataset, model specification, country and time period studied. Nevertheless it is helpful to set out the range of estimates which are in the current literature.

The overwhelming majority of the literature focuses on the returns to investment in R&D (the top row of **Figure 2**) rather than wider intangible or knowledge investments (the bottom row). We therefore begin with an overview of the estimates of private and social returns to R&D, before looking at the evidence on the returns to wider intangible investments.

2.2.1 Private returns to R&D investment

Papers using the production function methodology

Table 1 summarises the evidence on the private returns to R&D investment.[11] These studies all draw on the production function methodology, and estimate returns either by modelling stocks or flows of knowledge capital, or by

[10] There are two very recent reviews (Hall, 2011; Hall and Mohnen, 2013) which look at the links between R&D investment and 'innovation' and then the impact of 'innovation' on output or productivity. These lend themselves to an analysis of the importance of innovation for output but not to direct estimation of the returns to knowledge investment. We draw on the papers cited in these reviews where relevant when we look below at the direct and indirect evidence on how the returns to investments vary along a number of different dimensions.

[11] The papers include some estimates of elasticities which are not translated into returns; we exclude those from the table.

implementing a "dual" approach which assumes that firms are profit maximising, and estimates profit or cost functions rather than the production function.[12]

We group estimates according to the unit of data analysed (firm, industry or country) and conduct a separate analysis for a small number of UK-specific studies.[13] In total, our sample includes 55 studies providing 109 estimates of private returns to R&D, dating from 1984 to 2009. Of these, 5 are UK-specific studies (12 estimates) using UK firm or industry data. Of course, a number of the papers using country-level analysis will include the UK in their sample as well.

Table 1. Estimates of private rates of return to R&D investments

Level of analysis	No. papers	No. estimates	Min return	Max return	Median	Mean[14]
All studies						
Firm	30	60	0%	173%	26%	33%
Industry	16	30	7%	315%	24%	28%
Country	9	19	6%	123%	16%	29%
UK-specific						
Firm	4	10	11%	108%	39%	31%
Industry	1	2	12%	20%	16%	16%

Source: Frontier Economics based on Hall et al. (2009) and EC (2005)

Some papers provide multiple estimates of the rate of return, usually because a range of figures are presented representing different methodological assumptions or results for different cuts of the data. We capture the individual estimates presented for each paper; where a range is given we include the upper and lower points as two separate estimates from the paper.

As is clear the range of estimated returns is very large. However, whatever the unit of analysis, the mean rate of return is typically around 30% with median returns being slightly lower, typically 20 to 25%. Interestingly, there is little evidence that the private returns are higher when we use more aggregated units of analysis (countries over industries over firms); if private returns at an industry level are akin to social returns at a firm level we might have expected to see this

[12] See Hall et al (2009) for more details of the dual approach.

[13] Firm-level studies also include some studies based on plant-level data (firms may operate multiple plants).

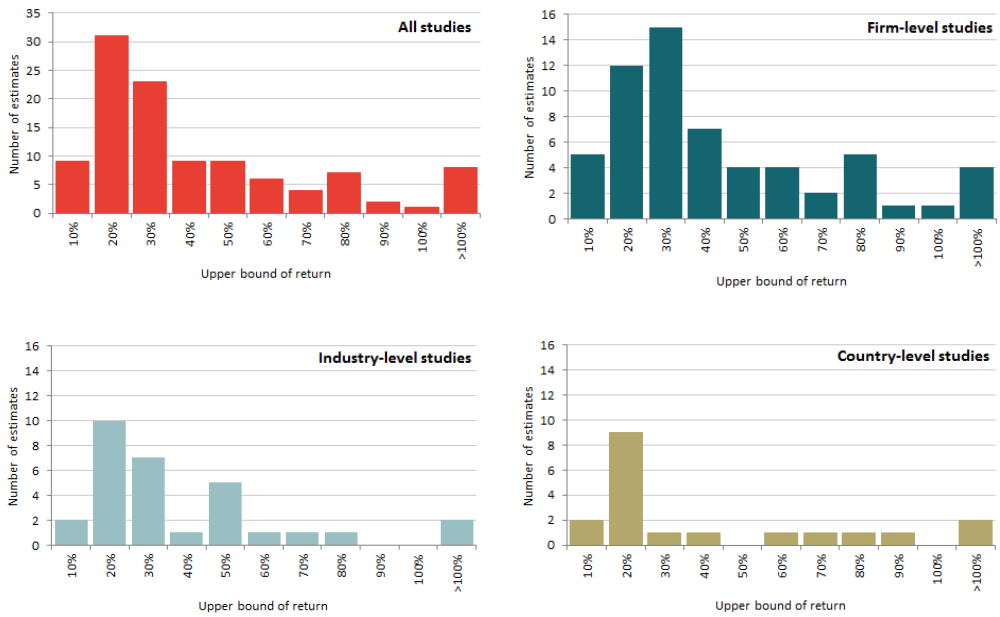
[14] The mean excludes estimates larger than 100%.

pattern. However the estimates will clearly be sensitive to the data sources, industries and periods studied, and within each level of analysis there is a wide range of estimated returns.

Relatively few papers rely on UK data for the analysis. It is somewhat difficult therefore to draw strong conclusions on whether the UK-specific studies produce higher rates of return than is 'typical' in the wider literature. Looking just at the firm-level studies, rates of return from UK specific studies appear to be around 30 to 40%, slightly higher than the average across all studies. Given the paucity of evidence it would not appear sensible to rely on UK-specific results for any policy analysis. Nor is it clear that we would expect rates of return to differ substantially in the UK as compared with other OECD countries.

Figure 4 below shows the distribution of the estimates, again grouped by the unit of analysis. The horizontal axis shows the return (grouped into bands of 10%, e.g. the first bar represents returns between 0 and 10%, the second between 10% and 20%, and so on); returns in excess of 100% are shown in a single column. The vertical axis shows the number of estimates within each range. In the top-left box, all the studies are shown together. Estimates for firm-, industry- and country-level studies are then shown in separate boxes.

Figure 4. Distribution of estimated private rates of return to R&D investments, by unit of analysis



Source: Frontier Economics based on Hall et al. (2009) and EC (2005)

Modal values of private rates of return to R&D across all studies are around 10-20%, though for firm-level studies the modal values are around 20-30%. There is some evidence of a tail of papers estimating quite high rates of return, in excess of 75%. However there is no particularly compelling evidence that private returns estimated using different units of analysis (firm, industry or country data) yield very different distributions of findings. Of course this could be driven in part by there being relatively few studies, particularly based on country-level data.

Papers using other methodologies to estimate private rate of return

A more recent paper by Doraszelski and Jaumandreu (2013) takes a rather different approach to estimating the private returns to R&D investments. They estimate a structural model in which firms invest optimally in knowledge and physical capital in the face of uncertain returns (in the form of productivity gains) but with some expectation of what the future returns will be. Using data from almost 1,900 Spanish firms in the 1990s, they estimate net private rates of return (after depreciation) of around 40% on average, which vary from 10 to 65% across industries (10% in food, drink and tobacco; 65% in metals).

Interestingly, they compare their estimates of private returns to those which would come from applying a traditional production function estimate to their data. Typically, the returns from the production function method are much higher (net returns between 54% and 200% across different industries).

This finding does not necessarily imply that a production function approach gives upwardly-biased estimates of the rate of return. The evidence comes from only a single study and so the result may be specific to the dataset used. Further, in one of the ten industries studied (timber and furniture) they find a lower net rate of return using the production function methodology. However the finding does suggest a degree of caution should be exercised when using estimated private rates of returns for policy purposes.

2.2.2 Social rates of return to R&D investment

Papers using the production function methodology

A number of studies estimate the social rates of return to R&D investments. These studies account for spillover effects from private R&D spending; as noted earlier they do not pick up wider social returns through e.g. the "public goods" aspect of some innovations leading to improvements in health or increases in public sector efficiency.

The usual method used to estimate social rates of return is to include some measure of 'external knowledge' in the production function, which is a weighted sum of the knowledge capital of other firms, industries or countries as appropriate to the level of analysis and the data available. As noted by Hall et al. (2009), the estimates of social returns can be sensitive to the weighting applied.[15]

Though it may seem obvious that social returns do exceed private returns, (and this has largely been borne out by the literature) from a theoretical stand point, this does not necessarily have to be the case (Cameron, 1998). There are four externalities that can arise from the invention of new goods and processes. Two are positive:

- **Knowledge leaks and spillovers**: the most typical view of spillover effects, in which other firms benefits from knowledge created by a given firm (or indeed 'public' knowledge created by publicly-funded R&D);
- **Surplus appropriability**: because of imperfect licensing, firms cannot appropriate the full economic benefits of their innovations, meaning that wider increases in producer and consumer surplus are not fully captured by monopoly profits.

However, two possible externalities are negative:

- **Obsolescence**: new products and processes make old ones obsolete or less valuable, and so could destroy some previous social value ('creative destruction');
- **Duplication and substitution**: there is a risk that some knowledge investments are duplicated. If the new products or processes are highly substitutable then the investments will be relatively inefficient: it would be more socially valuable for the research efforts to be redirected.

Because ex ante it is not clear whether positive or negative externalities dominate, empirical evidence on the social rates of return is important.

Table 2 below sets out a summary of the estimated social rates of return to R&D investments, again grouping the results by the underlying unit of analysis. Note that this table *only* includes estimates from studies which estimated social rates of return directly, and so direct comparisons between the figures in **Table 1** and **Table 2** is unwise.[16]

Where a social rate of return is provided directly, we follow the same methodology adopted for our review of private returns, taking all the estimates provided for a single paper, or the upper and lower bounds where a range is

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[15] An external knowledge variable representing public knowledge stocks generated from public sector knowledge investments can also be created and explored in this framework. We look at evidence on returns to publicly-funded investments in Section 2.3.1.

[16] For example, the median social rate of return in **Table 2** for studies at the firm level is lower than the median private rate of return at the firm level shown in **Table 1**. This does not mean that spillovers are negative at the firm-level, but rather reflects the very limited literature using firm-level data to estimate social rates of return to R&D at the firm level compared to private returns.

presented.[17] Where results are presented as separate estimates of private rates and return and 'external' rates of return, we estimate the social rate of return by summing the two (taking mid-points if a range is presented).

Most of the studies use industry-level data to estimate the returns, suggesting that the resulting estimates of social rates of return should be approximately "national" (allowing for spillovers across industries). The range of estimates is large – social rates of return in these studies vary from around 11% to 140%.[18]

Table 2. Estimates of social rates of return to R&D investments

Level of analysis	No. papers	No. estimates	Min return	Max return	Median	Mean[19]
Firm	1	4	17%	26%	22%	22%
Industry	11	15	11%	140%	50%	49%
Country	3	9	14%	155%	85%	44%

Source: Frontier Economics based on Hall et al. (2009) and EC (2005)

While it is difficult to read too much into the figures based on firm- and country-level data given the smaller numbers of estimates, there does appear to be some evidence that as the unit of analysis gets more aggregated, the magnitude of social returns increases: at the median, for example, social rates of return are 22% for firm-level studies, 50% for industry-level and 85% for country-level.

Where studies cite both private rates of return and external rates of return, we are able to get a sense of the relative size of spillovers compared to private returns. In general, spillovers are found to be positive, suggesting that social returns exceed private returns. **Table 3** summarises estimates of the ratio of social to private rates of return to R&D investments for those papers which provide estimates of both. Again, there is a considerable range of estimates, but focusing on studies at the industry level (where social rates of return approximate "national" returns to R&D investment), the social rates of return are typically around 2 to 3 times as large as the private returns.

This is roughly in line with evidence cited in Griffith (2004) who compares three studies using industry-level data to look at private (within-industry) and external

[17] Multiple estimates from a single paper often reflect different methods used to estimate the weighting factors when constructing the measure of "external knowledge".

[18] A single estimate from Odagiri (1985) contains a vast range of external returns between -606% and +734%; we ignore this outlier.

[19] Excluding estimates in excess of 100%.

(across-industry) returns. Again, the private returns are typically around one-half or one-third as high as the external returns.

Studies at country level (which pick up international spillovers) typically find smaller gaps between private and social rates of return. For example, Kao et al. (1999) use data from 22 countries, and find that private returns (at the national level) are much larger than external returns (across countries). They estimate private rates of return of around 120% compared to social rates of return of 149%, implying external returns of only around 29% flowing across borders.

Table 3. Ratio of social to private rates of return to R&D where both estimated

Level of analysis	No. papers	No. estimates	Min ratio	Max ratio	Median	Mean
Firm	1	4	1.4	2.1	1.8	1.8
Industry	11	15	1.0	8.1	2.4	2.9
Country	3	3	1.3	1.6	1.3	1.4

Source: Frontier Economics based on Hall et al. (2009) and EC (2005)

Studies using other methodologies

Some other studies have explored the importance of international spillovers though without using the same methods which would allow the estimates to be captured in the table above. Naveed et al. (2013) investigate the relative strength of intersectoral and international spillovers, using data from 13 OECD countries between 1988 and 2006. They find that domestic intersectoral spillovers are stronger than international spillovers from firms in the same sector but different countries. Nevertheless, they find that both international and domestic R&D knowledge spillovers are significant.

Griffith, Harrison and Van Reenen (2006) investigate the spillovers that occur between the US and the UK using a dataset of UK and US data matched to patents data. They conclude that UK firms' total factor productivity would have been at least 5% lower in 2000 without US R&D growth in the 1990s. However, the converse relationship was not found showing that the effects of international R&D spending can be asymmetric. The impact is larger for UK industries which are estimated to be further behind the 'technological frontier' of their US counterparts; this suggests that part of the spillover effect from R&D investment is about learning from more advanced countries or firms as much as it is about shifting out the frontier of technological advancement.

2.2.3 Rates of return to wider intangible investments

As discussed in Section 1.2.3, investments in science and innovation go beyond scientific R&D expenditures. However there is relatively little evidence on the rates of return to wider intangible investments in the same sort of way as exists for R&D investments, largely reflecting (at least until recently) a relative lack of data on such spending.

Some recent studies have looked at wider issues relating to intangible investments. At present (with some exceptions), these investments tend to be treated as intermediate inputs into GDP, and therefore not included explicitly as a final component of GDP unlike investments in physical capital which are counted as part of the investment component of GDP statistics.[20] The innovation of these papers is to adjust the national accounts datasets to correct this omission. Corrado et al. (2005) estimate that up to $800 billion of intangible investments were excluded from measured US output data. They find that when intangible investments were considered, productivity growth rates were higher than previously estimated. Van Ark et al. (2009) expanded this concept to European countries and conclude that intangible assets account for around a quarter of labour productivity growth in the US and larger European countries; for smaller countries, intangible assets were less important. Corrado et al. (2012) find that in the US, UK, Sweden, Netherlands, Ireland, France, Denmark and Austria, intangibles accounted for around the same proportion of productivity growth (measured as output per hour worked) as tangible capital investments.

Relatively few papers have tried to estimate rates of return to wider intangible investments directly.[21] Haskel and Wallis (2010) apply the thinking behind Corrado et al. (2005) to an aggregate UK dataset which includes wider measures of intangible investment (including scientific R&D) alongside input and output data for a number of industries in the private sector. Using a production function framework, they find no evidence that measures of total intangible investments by firms in these sectors are related to aggregate private sector TFP growth. The interpretation of this is that they find no *spillover effects* from intangible investments (social returns do not exceed private returns), not that there are no returns at all from intangible investments.[22] Note that this includes scientific

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20 Note that the UK Office for National Statistics is moving towards a new international standard for measuring GDP (ESA10) which will incorporate R&D spending into National Accounts measures. See http://www.ons.gov.uk/ons/guide-method/development-programmes/esa2010/index.html.

21 London Economics (2012) summarise evidence on the links between intangible investments and spillovers, but do not focus explicitly on economic rates of return to such investments.

22 Their dataset adjusts measured TFP growth in each industry for intangible investments, meaning that private returns to such investments are already accounted for.

R&D; their estimate therefore does not accord with many of the papers summarised in **Table 3** which tended to find evidence of R&D spillovers.[23]

In a more recent paper, Goodridge et al. (2012) conduct a similar analysis using data on intangible investments for seven UK industries between 1992 and 2007. They construct stocks of external R&D and other intangible assets which are added to a production function, and estimate their relationship with industry level TFP growth. Weights to construct external stocks are based either on intermediate consumption flows or labour market flows between industries. They find positive and significant effects of 'external R&D' on TFP growth, suggesting evidence of cross-industry spillovers (though their figures report elasticities rather than rates of return). They also find positive and significant effects for 'external non-R&D intangibles', again suggesting positive spillover effects, though the result is somewhat less robust to the choice of weighting than the result on external R&D. Interestingly, they find significantly *negative* effects from non-R&D intangible investments *within* an industry which would suggest negative private rates of return to these wider intangibles. It is not clear what might be driving this, though the authors note the result disappears when financial services (where it may be more difficult to measure outputs accurately) are excluded from the model. The paper tries to estimate which sorts of wider intangible investments might be associated with the results, though as they tend to move together over time there are significant multicollinearity problems which make this difficult to estimate. They suggest their most robust findings are that it is economic competencies (branding, market research, firm-specific human capital and organisational structure) which drive the overall result on non-R&D intangibles, with limited evidence of significant private benefits or wider spillover benefits from investments in computerised information (software and databases) or intellectual property (design, non-scientific R&D, mineral exploration).

2.2.4 Summary

In Section 1.2.3, we suggested that for policy purposes, the most useful "rate of return" estimates would encompass returns at the economy level from a marginal investment in science and innovation, defined broadly as investment in intangible capital. This would include spillover benefits in the private sector, and wider returns accruing to society from the public good benefits of such investments.

None of the existing evidence on the rates of return is precisely of this nature. The majority of economic studies which have looked at the rates of return have

[23] Though it is worth noting that some other industry-level studies have found little evidence of spillovers from R&D investments. For example, Wolff and Nadiri (1993) find that social rates of return are no higher than private rates of return based on industry-level data and using capital inputs as a weighting matrix to construct external knowledge stocks. Bernstein (1998) finds similar results for Japanese industries. Note that in both papers, some specifications of their results do find evidence of spillovers; we capture all relevant specifications in our estimate summary above.

been the private returns to private sector R&D at the firm level. These studies have yielded estimates in the range of 25 to 30%, broadly consistent with the estimates of private returns to R&D for studies estimated at the industry- or country-level. A number of studies have also tried to estimate spillover effects from R&D investment, and have typically found them to be large and significant. Social rates of return to R&D (the sum of private and spillover effects) tend to be around 50% when looking at spillovers across industries, which give the measure closest to the 'national' returns to private R&D investments. Studies which estimate both private and social returns tend to find that social returns are around 2 – 3 times as large as private returns.

The evidence on the returns to wider, non-R&D intangible investments which might also help to drive innovation is much narrower; indeed no studies have estimated a direct rate of return. There is very limited evidence that these other intangibles have particularly significant, positive spillover benefits, and indeed somewhat limited evidence on whether they have significant private returns. However given the limited evidence base on wider intangible investments it seems too early to draw any particularly firm conclusions on whether their private or social rates of return look different from those in R&D.

2.3 Variation in rates of return by type of investment

This section discusses evidence for how returns to investment in knowledge vary across a range of different dimensions suggested by the framework set out in **Figure 3** above. We focus on two issues where the literature appears to be most well-developed:

- Social returns to publicly-funded R&D investments;
- Private returns to investments in product and process innovation;

As a general point, it is worth noting that relatively little of the literature explicitly compares estimates of the rates of return to knowledge investments across these different dimensions; we therefore include more suggestive evidence in our analysis in this section.

2.3.1 The returns to publicly-funded R&D investments

There are three main ways in which the government can be involved in the production of knowledge through R&D investments (Guellec and De La Potterie, 2003):

- Directly conducting the research themselves (through public research centres, or universities);
- Offering fiscal incentives (such as taxes and subsidies) to encourage research and development;

- Allocating grants to private companies to conduct research.

Money invested by the public sector in offering fiscal incentives or grants to companies to conduct R&D can lead to private returns for the firms who do so, as well as social returns through wider spillover benefits as described in Section 2.2.2. R&D which is conducted directly by the public sector will, by definition, yield only social returns, either through its benefit to private companies who can draw on the knowledge produced to increase their own profit or productivity, or through its wider (and harder-to-quantify) benefits on the productivity of the public sector, or on national health, defence and so on.

Most of the literature which has explored the returns to publicly-funded R&D investments has looked at the impact on private sector output or productivity, again drawing on a production function methodology. Other approaches, including surveys and case studies, have also been used both to look at the importance of public funding for the private sector, or to try and quantify some of the other ways in which publicly-funded R&D can generate social returns.

Evidence from production function methodologies

A significant amount of early evidence focused on the effect of spending on government research programmes in agriculture on productivity in that industry. Salter and Martin (2001) summarise 9 studies conducted between 1958 and 1993. These found social rates of return estimated at between 20% and 67%, with typical values around 30–40%. Thus public R&D investments targeted on a particular industry do appear to increase productivity in that industry.

Other studies outside of agriculture have found less compelling evidence of significant returns to publicly-funded R&D (for a summary, see **Table 14** in Appendix B). This might be explained by the methods used. Many studies use firm- or industry-level data and look for any variation in the impact of R&D conducted privately according to whether it was publicly or privately funded. However, we might expect that publicly-funded R&D conducted by private industry is quite different in nature to privately-funded R&D: these may be projects characterised by longer lags, or greater uncertainty, for example.

Fewer studies have looked at the impact on the private sector of R&D investments conducted by the public sector. Haskel and Wallis (2010, 2013) explored how social returns to public sector R&D vary according to whether the investments are made through government departments, research councils or higher education. They use a standard production function approach together with aggregate time series data to look at the impact of these investments on later private sector productivity growth. They find that research council investments are strongly positively correlated with private sector productivity growth, but no evidence that other forms of investment have similar impacts on private sector productivity. Haskel et al. (2014) use industry-level data, measures of the extent to which industries engage with publicly-funded science and aggregate measures of public R&D investments made by research councils, higher education and government departments, and again estimate a production function to assess whether public investments impact private (industry-level) productivity. They find that this (aggregated) measure of public investment yields a social rate of return of around 20%, through its impact on private sector productivity, and as we note below there may be other non-measured impacts from these investments suggesting that the total social returns are somewhat higher.[24]

The econometric analysis we carry out in this report (see Section 3) extends the Haskel and Wallis (2010, 2013) analysis, drilling down further into the types of research council investments which are most strongly correlated with private sector productivity growth. We find that the most consistent benefits to private sector productivity appear to come from science-based, applied research council investments, which are potentially closer to the sorts of investments private industries themselves would carry out.

This should not be interpreted as evidence that the social return to other public R&D investments is zero or has no benefit to the UK economy, for a number of reasons:

- It is possible that returns to investment in public R&D conducted by government departments or higher education institutions are harder to capture in private sector productivity, certainly over short time horizons. For example, there may be long lags between university research and productivity-enhancing private sector innovation. However, the production function methodology typically relies on a short data period which makes it hard to pick up lengthy lag profiles.
- There is a close interdependency between higher education funding and research council funding, as illustrated by Hughes et al. (2013). Research council investments going to academic institutions exceeded £1.5 billion in 2010-11, for example.
- Public investments may have social returns through their impact on the public sector (better education, health or defence outcomes) or the efficiency of public service delivery which would not show up straightforwardly in private sector productivity.

More generally, even if we look at social returns purely through the lens of how publicly-funded R&D affects private industry productivity, there are many reasons why we might expect to find relatively low numbers. These include:

[24] Haskel et al. (2014) also note that this 20% figure excludes the potential crowding in of additional private sector R&D from increases in public R&D (see Section 2.4.1).

- A greater focus on **basic research** in publicly funded R&D[25] than privately funded R&D.[26] The returns to basic research may be more **uncertain** (since immediate applications are not clear) and likely to emerge with much longer **time lags** (since they can be made commercial only once the new knowledge has been absorbed by the private sector).

- Difficulties in **attribution**: the private sector will devote R&D investments to absorbing knowledge created through public funding; any returns to this may be attributed entirely to the private investments.

- Public R&D may not be **aimed** at increasing private sector output, at least not directly. Rather, as discussed above, the value of public R&D investments may be felt in areas such as public health, defence and the efficiency of public service delivery, all of which yield economic returns but which are not well-captured in a standard methodological framework to estimate returns.[27]

Given the lack of a long time series of productivity and investment data, coupled with difficulties in measuring the wider social impacts of research investments or the efficiency of the public sector, the production function approach used is the best available methodology to explore the empirical relationship between public investments and private sector productivity, but the caveats above as to what it can realistically tell us about the nature of social returns to public investments are hugely important to bear in mind. Other methodologies, including case studies and qualitative evidence, or bespoke data collection, can help to fill in some of the gaps about the wider benefits of publicly-funded R&D, as we now consider.

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[25] In the UK in 2011-12, for example, it is estimated that just over 60% of research council funding went towards 'basic' research (BIS SETS statistics, Table 2.6). "Basic" research includes both 'pure' basic research, defined as investment to advance knowledge without a clear expectation of future long-term economic benefits; and 'orientated' research which is knowledge expected to help solve identified or expected problems. Of the Research Council funding in 2011-12, around 63% of the basic research spend was 'orientated'.

[26] Estimates from 2012 for business R&D suggest that only 5% of private sector R&D is basic (see Table 5 of ONS Business Enterprise Research and Development (2012), http://www.ons.gov.uk/ons/dcp171778_337993.pdf.) There is evidence (Mansfield, 1980; Griliches, 1986) that private sector basic R&D investments are associated with high returns in terms of output or productivity growth, though it is unclear whether this represents reverse causality in that more successful firms are more able to 'afford' the luxury of investment in basic research, given the uncertainties and difficulties in appropriating the returns from basic research outlined in this section. Czarnitzki and Howarth (2012) analyse firm-level data in Belgium, and find that investment in basic research is more productive for high-tech firms such as those in chemical, drug, computer, electronics and instrument industries than for low-tech firms.

[27] It is notable that in at least two studies, public investments were found to have significant, positive returns once defence R&D spending was excluded (Leonard, 1971; Guellec and De La Potterie 2003), since defence research spending is a clear case where we would not really expect direct benefits for the private sector.

Evidence from other methodologies

These measurement difficulties have led to a number of alternative approaches to estimate the returns to publicly-funded investments in R&D. One approach was pioneered by Mansfield (1991), based on survey evidence asking firms about their use of publicly-funded basic (academic) research in their innovative activity. He surveyed 76 major US firms in the period 1975-1985 in 7 manufacturing sectors and investigates the value of the outputs from these firms that could not have existed without recent academic knowledge (created within the 15 years prior to the product and process innovations generating the output). He found that about 10% of new processes and products would not have been developed without academic research, and estimates a social rate of return to the academic investment of around 28%.[28]

Other studies have adopted a similar approach. For example, Beise and Stahl (1999) obtained survey responses from 2,300 German firms in the period 1993-1995 to find that around 10% of new products and processes (representing 5% of total sales) could not have been developed without public research, consistent with the Mansfield estimate. They find that 14% of new products from R&D intensive firms could not have been developed without recent academic innovations. For new processes, this number was 5.2%.

Cohen et al. (2002) use data from the Carnegie Mellon Survey – administered in 1994 on a sample of R&D managers in US manufacturing firms – to evaluate the role of public research in industrial R&D. Among other findings, they suggest:

- Around 30% of R&D projects make some use of public research. Public R&D is seen to be particularly important for larger firms and start-ups, suggesting that mid-sized firms make less use of it.
- Public research is cited as important in driving R&D project completion by 36% of respondents, with particularly high importance in the pharmaceutical, aerospace, and automotive industries.
- Public research in engineering, computer science and medical science is seen as having the largest impact on private R&D projects, relative to research in mathematics and natural sciences. The latter may be more often "basic" in nature and so less close to market.
- Publications are the dominant channel for the transfer of information from public to private R&D. 41% of respondents rated publications as at least moderately important as a channel of information for a recently completed "major" R&D project. Informal information exchange, public meetings or conferences, and consulting follow closely, being rated as at

[28] Note this is an average rather than a marginal rate of return; thus it does not necessarily follow that an additional £1 investment in academic research would yield £0.28 in returns.

least moderately important by 31 to 36% of respondents. Licenses and university-industry cooperative ventures tend to be less important.

Another approach has been the use of case study evidence, where the returns to a particular public investment (usually a big academic research programme, or a large scientific facility) are evaluated (some examples are summarised in **Table 15** in Appendix B). The degree of sophistication of such analyses varies across studies. At a basic level, the study estimates the total amount spent (e.g. on the facility) and uses multiplier analysis to estimate the total additional (indirect and induced) impacts on the wider local or national economies (for example, STFC (2010) estimate that £1 spent on a large science facility in the North West generated an additional £0.67 of indirect and induced impact). This generates estimates of the social returns to the initial investment but it is not clear whether these are higher or lower than the returns which could have been obtained through other uses of the investment. Other studies have tried to quantify some of the wider social benefits of the investments, such as gains to public health. For example, the Wellcome Trust (2009) estimates that spending on cardiovascular research generated health gains equivalent to returns of about 9% per year.

2.3.2 Private returns to product and process innovation

A considerable body of evidence has tried to distinguish between the private returns to "product" and "process" innovations. A product innovation occurs when a new or improved good or service generates a new source of demand, whereas a process innovation is one which improves the production method for an existing output. Depending on the outcomes of interest, we might *a priori* expect that process innovations would have a greater effect on measured productivity and product innovations a greater impact on the value of sales or output. New products may lead to short-run adjustment costs that lower productivity in the short run. However, process innovations could generate lower prices (and so lower revenue, at least in the short-run before demand expands for goods with elastic demand) whereas product innovation could yield temporary monopoly profits (through either patents or in the period before other firms imitate the product) which yield higher revenues.

The evidence on the rates of return to product and process innovations is somewhat mixed. Before discussing that, however, it worth noting that the literature has taken two broad approaches to this question. Some studies (see Hall, 2009) look at decomposing R&D investments into 'product' and 'process' R&D and seeing which yield the greater returns in a production function estimation. Other studies (see Hall, 2011 and Mohnen and Hall, 2013) instead model the returns to product and process *innovations*, and treat total R&D

investments as an input into these innovations.[29] These different methods appear to yield somewhat different findings.

Studies looking at the returns to product and process R&D investments directly tend to find that *process R&D yields higher returns*.

Griliches and Lichtenberg (1984) use data from US manufacturing firms between 1958 and 1978. Their R&D measure is split between product- and process-oriented elements and 'imported' R&D from other industries. They find that process R&D has a larger effect on a firm's productivity than product R&D (though typically both have positive, significant effects). In a later study of manufacturing firms in Canada between 1974 and 1989, Hanel (2000) also investigated the relationship between industry's own R&D expenditures and TFP growth. The same result is found: the effect of process-related R&D is significantly higher than that of product-related R&D.

On the other hand, the literature which takes an indirect approach by modelling product and process innovations as a function of R&D spending generally finds that it is *product innovation which yields the largest benefits*.

Griffith et al. (2006) study data from France, Germany, Spain and the UK from 1998 to 2000. They find that productivity elasticities of product innovation are positive and significant in France, Spain and the UK. Process innovation, on the other hand, only has a positive and significant effect on productivity in France. However they find no evidence that either form of innovation has a negative productivity effect. Mairesse and Robin (2008) analyse data from French firms between 1998 and 2004. They find evidence of significant, positive productivity impacts of product innovation in the manufacturing and service sectors, but no positive effects of process innovation. Indeed, they find some evidence of *negative* effects of process innovation for process innovation in the manufacturing sector between 2002 and 2004. Hall et al. (2009b) analyse data from Italian firms between 1992 and 2003, finding that process innovation has no significant productivity effect whereas product innovation has positive, significant effects.

How can we reconcile these seemingly-contradictory results? The answer may relate to measurement. It is difficult to disentangle product and process R&D, and so hard to categorise a particular pound of R&D investment as being directed towards new "products" or "processes".

On the other hand, while it may be more straightforward to identify a particular form of innovation as a new product or new process, Hall and Mohnen (2013) caution that process innovation tends to be more poorly measured in survey data.

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[29] Innovation outcomes are typically measured on the basis of survey responses, patenting behaviour and so on. Studies create indicator variables for whether or not a firm carried out a product or process innovation, or create more continuous innovation measures. These studies normally use the CDM model described in Appendix 1.

It is possible to identify whether a particular firm engaged in process innovation or not, but it is hard to quantify the *value* of that innovation. In contrast, it is more straightforward for firms to estimate what proportion of their sales are accounted for by new products, which is a way to measure not only whether or not firms engage in product innovation, but also their value.

Both Hall (2009) and Hall and Mohnen (2013) also note that whether looked at in terms of R&D inputs or innovation outputs, there is a high degree of collinearity between new products and processes which can make econometric estimation challenging.

2.4 Wider influences on the rates of return

In addition to breaking down the rates of return to investment along different dimension, the literature on the relationship between innovation, R&D and productivity also identifies other aspects that might influence the return on investment. This section will discuss evidence on:

- The extent to which public R&D investment encourages additional private investment (crowding in) or discourages it (crowding out);
- The lags between investments and innovation outcomes;
- The influences on knowledge spillovers across countries;
- The role of linkages between business and researchers in generating returns to research investments.

2.4.1 Crowding in and crowding out

We noted in Section 2.3.1 that there was some evidence that the social returns to publicly-financed R&D (at least in terms of the impact on private sector output) were lower than those to privately-financed R&D, but that there were methodological reasons why the social returns to public R&D are difficult to measure. Another way in which public funding of R&D (whether direct funding for research carried out by the public sector or private sector, or financial incentives for the private sector to carry out R&D) could generate social returns is through its impact on R&D in the private sector.

The key issue is whether public support for R&D leads to additional private R&D (crowding in) or substitutes for private R&D which would otherwise have occurred (crowding out). Crowding out could occur for two main reasons:

- Government spending may simply substitute for private R&D financing which would otherwise have occurred rather than leading to genuine 'additionality' in total R&D spending;

- Government spending may crowd out private R&D by increasing the demand for research capital and labour inputs, raising their factor prices and therefore making it more expensive for private firms to invest.[30]

We consider three forms of public spending on R&D: fiscal incentives; public subsidies; investment in R&D carried out directly by the public sector. Most of the evidence suggests that fiscal incentives and public subsidies for private sector R&D do generate additional private investments, while the evidence on the impact of R&D carried out by the public sector is more mixed. We look at the evidence for each type in more detail below. However, it is worth noting that there is limited scope for comparing the size of the effects for different types of public R&D investment. Only a limited number of studies have taken into account more than one type of spending, and the "units" used to measure the size of public support for R&D of different types are not straightforwardly comparable. For example, research on the effect of tax incentives has generally estimated the effect of a marginal increase in the 'generosity' of these tax incentives, measured in different ways, whereas subsidies and direct public R&D are usually measured as the impact of a marginal pound of additional spending.

Before looking at different forms of public support for R&D, it is worth highlighting a review article by David et al. (2000) who examined the evidence base (at that time) on the extent to which public and privately funded R&D investments appear to be complements (which would imply crowding in) or substitutes (crowding out). They survey around 33 results: around two-thirds find evidence of complementarity and one-third substitution. Substitution was more common in studies based on disaggregate data (firm-level or lower) and in studies based entirely on US data (which may reflect specific issues related to the US system of support for R&D). They note in general that the literature is not always that compelling in *how* the degree of complementarity or substitution between private and public R&D investments is calculated: there is little evidence that uses properly experimental (or quasi-experimental) approaches, for example. Instead, the literature relies on correlating private and public R&D in various ways, hoping to capture possible endogeneity biases through the inclusion of sufficient control variables or finding appropriate instruments.

Fiscal incentives for private R&D

Falk (2006) summarises a number of studies looking at the factors associated with private sector R&D intensity (the proportion of turnover spent on R&D). Tax incentives are found to increase private sector R&D intensity.[31] Their own

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30 There is an issue as to how international the market for research capital and labour is and whether spending by a small country on public R&D is sufficient to affect factor prices.

31 A positive impact of tax incentives results from a negative correlation between private sector R&D intensity and a measure of the after-tax "price" of R&D, which falls when the tax incentives become

empirical estimates based on data from a panel of OECD countries between 1975 and 2002 suggests that a 1% increase in the generosity of tax incentives leads to a 0.22% increase in private R&D intensity in the short-term, and a 0.84% increase in the long-term. This is similar to Bloom et al. (2002) who find a 1% long-run increase in private R&D intensity following a 1% decrease in the R&D user cost of capital determined by tax incentives. Guellec and de la Potterie (2003) use a dataset of 17 OECD countries from the period 1981 to 1996, and again find that fiscal incentives for private R&D spending lead to additional spending. However they find a smaller impact: a 1% increase in the generosity of R&D incentives is estimated to increase private R&D intensity by around 0.31% in the long-term.

Public subsidies for private R&D

In terms of direct R&D subsidies, the evidence also generally points to crowding in effects. Scott (1984) finds that increases in the government-financed R&D share in a firm's revenues are associated with higher private R&D shares, and that this result is robust to company- and industry-effects being controlled for.[32] Guellec and de la Potterie (2003) find that a $1 increase in direct public funding for private sector R&D translates into an increase in private R&D of around $0.70 in the long run. Aerts and Schmidt (2008) analyse Belgian and German data between 1998 and 2004, finding no evidence of any crowding out effect from public subsidies for R&D. The subsidy is estimated to generate an additional 65% more expenditure on R&D and a 5% increase in R&D intensity. Falk (2006) finds some evidence that government-funded business R&D leads to increases in private sector R&D intensity, though with lower long-term elasticities (around 0.27 to 0.29) than the tax incentives. Their finding is also somewhat sensitive to the model specification.

As noted above, most empirical studies correlate private R&D measures to measures of the public funding they receive for R&D to investigate crowding out effects. González and Pazó (2008) use a different approach. They take a matching approach using Spanish data, comparing private R&D outcomes in firms that receive R&D subsidies from government to 'similar' firms that do not on the basis of observable firm characteristics. Their assumption relies on there being no *unobserved* reasons, correlated with their private R&D efforts, why firms receiving subsidies did so. Under that assumption, they find no significant evidence that subsidies stimulate additional private R&D, but nor do they reduce

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more generous. The established measure of after-tax R&D price is the so-called "B-index", developed in Warda (2002). This is defined as (1-A)/(1-t), where A id the discounted present value of tax credits and other allowances on R&D assets, and t is the corporate tax rate.

32 These fixed effects try to control for concerns that government-financed R&D tends to flow to firms or industries that are themselves already more R&D-intensive, thus creating a spurious positive correlation.

private R&D that would have taken place anyway without the subsidy. Instead the public R&D funding is just added to the private R&D activity of the firm.

Clausen (2009) uses Norwegian data from 1999 to 2001 to investigate whether there is a difference in the effect of subsidies for 'research' (further from the market) compared to subsidies for 'development' (closer to the market). The study finds 'research' subsidies to be positively correlated with 'research' expenditure, and 'development' subsidies to be negatively correlated with 'development' expenditure. This result potentially suggests that policy should focus on earlier research, as subsidies for closer to the market activities may substitute, rather than stimulate, private investment. However, the empirical approach adopted in the study relies on an assumption that the total industry-level value of development subsidies is not correlated with firm-specific private investments, which may not be the case (for example, if there are intra-industry spillovers of knowledge). Further research exploring the distinction between more basic and applied research subsidies would be useful to validate this result.

The effect of public investment in private firms might also depend on the size of the public investment and the type of firm receiving public money. Gorg and Strobl (2007) use Irish data between 1999 and 2002, finding that the crowding in or out effects depends on the size of the firm and the size of any R&D incentives. They find no significant impact on private R&D for large, foreign multinationals, but a significant crowding in effect for smaller, national firms receiving relatively small R&D incentives. However if these firms received larger grants, then crowding out was observed instead.

R&D carried out directly by the public sector

The evidence on the impact of R&D carried out directly by the public sector is more mixed. Guellec and de la Potterie (2003) find that R&D conducted directly by the public sector results in less private R&D, though there was no significant effect from R&D conducted in higher education sectors. Falk (2006) finds that R&D conducted by higher education institutions leads to an increase in private sector R&D intensity, estimating an elasticity of around 1.0 in the long run. They suggest this translates into an additional dollar of higher education R&D generating an additional three dollars of private R&D in the long run ($0.60 in the short run). However, the significance of the result is again somewhat sensitive to the choice of model used.

2.4.2 Lags between investment and innovation

A number of studies have provided evidence on the 'typical' lag times between research investments and returns being realised. Of course the lags for any individual investment will be heterogeneous. The length of lag times (and, related to this, the length of time for which benefits from research investments persist) can have significant effects on the estimated returns to initial investments, and there is significant policy interest in how lag times can be reduced (House of Commons Science and Technology Committee, 2013).

Lags in private sector R&D

Pakes and Schankerman (1984) summarise some evidence on the average lags between private sector R&D and the beginning of a new revenue stream for the innovator. This lag depends on the time for R&D projects to be complete ('gestation') and the time for commercialisation of the resulting innovation ('application'). Mean lags are estimated to be around 1.2 years in the electronics sector, 1.7 years in chemicals and 2.4 years in the machinery sector (Rapoport, 1971). Other evidence suggests lags of around 2.2 years for firms in nondurable goods manufacturing industries, and 2.6 years for durable goods manufacturers (Wagner, 1968).

Rouvinen (2002) explores the importance of lag structure in production function models linking private sector R&D to productivity, using data from 14 industries in 12 advanced economies. He finds that lags of up to 4 years in R&D investments are associated (often most strongly) with current productivity outcomes.

There is, however, a great deal of variation in 'typical' lag times in different industries. As we note in our case study findings (see Section 4), for example, in key sectors like aerospace and life sciences, development times for new products (such as new drugs) or new technologies in aircraft design can be very long indeed, often well in excess of a decade.

Lags in public sector R&D

Existing evidence suggests that R&D performed in the public sector takes much longer to generate returns. This may reflect a larger share of public R&D investments going towards basic research without specific commercial application in mind, though of course there are often ultimately commercial benefits to public investments. Government funding does also support a significant amount of more applied research which might be expected to generate more rapid social returns.

Adams (1990) studies the lags between academic science investments and productivity growth and finds that there are statistically significant returns to academic sciences with very long lags (approximately 20 years).

Morris et al. (2011) survey a number of studies looking at commercialisation lags in medical research. This combines some studies which focus on lags following clinical trials, and others focusing on lags from new publications of different kinds; thus the evidence mixes lags from academic and non-academic research. Studies that appear to focus more clearly on lags from academic publication to some sort of medical advance suggest long lags. For example, Henderson and

Cockburn (1996) report a mean lag of 28 years between 'enabling scientific research' and new drugs being taken to market. Bales and Bohen (2000) find a mean lag of 17 years between 'original research' and implementation. Grant et al. (2000) find median lags of around 8 years between publications and new medical guidelines in the UK, whilst HERG et al. (2008) find mean lags between publication and guidelines of 9 to 13 years across different sectors of medicine. These estimates will underestimate the time from investment to outcomes since they ignore the time from research funding to publication.

Our case study findings from the life sciences sector (see Section 4.4) also find evidence of long lags between medical academic research and new innovation – for example, research on monoclonal antibodies in the 1970s was used to develop new approaches to treatments in the early 2000s which is still being developed in the present. This is not limited to life sciences – for example, in aerospace (see Section 4.3) we find examples such as chemical research into a super-alloy beginning in the 1980s which were not translated into new products for more than 20 years. These case studies also highlight the importance of different forms of public investment along the whole development cycle in these sectors, including basic research in underpinning science and investment in capital facilities which support the development of new products and technologies.

Mansfield (1991) reports survey evidence on the mean lags between academic publication and firms' introduction of new products and processes where the publication was deemed to be instrumental to the innovation. Again, this will ignore lags between public investments and the production of academic publications so will understate the lags from investment to commercialisation. Across all industries, he finds a mean lag of around 7 years, ranging from 4.2 years in the 'instruments' sector to 9.8 years in the metals sector, based on data from 1975 to 1985. In an update to the work (Mansfield, 1998) using data from 1986 to 1994, he finds similar results: a mean lag of 6.2 years, ranging from 5.2 years in the information processing sector to 8.5 years in the medical sector.

Even if lag times between investment and returns being realised are longer for public R&D, as noted by Haskel et al. (2014) there are still many ways in which public funding (e.g. through academia) can yield more rapid benefits to business productivity and help drive more incremental innovation. These include advice and consultancy services and the training and employment of PhD students.

How quickly do the returns to innovation fade away?

Some studies have tried to estimate how quickly knowledge capital "depreciates". As noted in Appendix A, this depreciation rate can be important in any empirical methodology designed to estimate rates of return.

Empirical estimates of depreciation are limited to firm-specific knowledge, drawing on a number of sources of evidence. For example, Pakes and

Schankerman (1984) use evidence from patent renewal statistics to estimate the rate at which the private returns from patented innovations decay over time. They estimate a decay rate of around 25% per year (that is, a patented innovation generating profits of £100 in year one would generate profits of £75 in year two, £56.25 in year three and so on), with a 95% confidence interval of 18 to 36%. However this is based on patent renewal data from the 1930s, and focuses only on patentable innovations. It is not clear whether the decay rate for other innovations would be expected to be similar, though as the authors note, the decision to patent is within the control of the firm and it might be expected that patents are only taken out where it would be expected to reduce the decay rate. This would suggest returns to non-patented innovations could decay more quickly.

Wagner (1968) surveys firms asking how long applied R&D-led product and process innovations last before they become obsolete. On average, the responses suggested that new innovations were expected to last around 8 to 11 years; from this, the authors estimate decay rates in the order of 20 to 30%, similar to the results based on patent renewals.

Corrado et al. (2009) summarise evidence on these depreciation rates from a number of other studies which range from around 12% to 26%. They suggest that around 20% is a reasonable consensus figure.

Note that none of these studies are clear on whether this is a constant rate of decay or whether (for example) returns may be steady for a time then decay rapidly, or decay more quickly in earlier years before levelling off. Further, since innovation usually builds on previous innovation, the returns can persist even if a particular innovation is rendered obsolete by new products or processes being introduced.

Our case study findings (see Section 4) drawing on discussions with firms in the aerospace and life sciences industries make clear that there can be considerable uncertainty over the profile of returns to a particular innovation. For example, whilst new drugs in life sciences are protected by patent, not all of the patent period covers a time when the drug is on the market such that the effective patent life is uncertain. In addition, the timing of new products which replace existing ones is very difficult to predict. Partly as a result, investment in some industries such as aerospace focuses not on a single product, but rather on developing new technologies with multiple applications, as a way of insuring against potential obsolescence from future innovation.

Nor does this evidence say anything about how quickly *publicly-funded* knowledge depreciates. Indeed, the most typical assumption in academic studies is a zero rate of depreciation for public knowledge since the knowledge is normally built on incrementally rather than being rendered obsolete by new innovations as happens in the case of firm-specific knowledge. This zero depreciation rate may be more appropriate for investments in basic research (which of course are not always publicly-funded) since the underlying scientific knowledge, once discovered, can reasonably be assumed to remain in place in perpetuity. Public investments in applied R&D may be subject to some deprecation, though presumably lower than the rate applied to private investments if the public investment is not on a new product or process for a single firm but rather on developing innovations with broader applicability.

Taken together, while there is evidence that particular firm-specific innovations can become obsolete over a relatively short period of around 10 years, this should not be taken to suggest that the benefits of innovation disappear in that time frame.

2.4.3 Factors influencing international spillovers

In Section 2.2.2 we discussed evidence for international spillover effects from R&D investments carried out in one country to other countries. A body of literature has examined factors which are associated with the size and prevalence of international spillovers. The main drivers appear to be:

- **International trade**: spillovers appear to be larger for countries that are closer trade partners (Coe and Helpman, 1995),[33] in particular import flows (Ang and Madsen, 2013).
- **Human capital**: cross-country spillovers mainly are increased when human capital (measured by average years of schooling) in a country increases (Bianco and Niang, 2012).
- **Participation in scientific networks**: Di Cagno et al. (2013) assess the impact of participation in the European Union Framework Programmes for Research, Technological Development and Demonstration. From a dataset of 31 countries (including the UK), they conclude that participation was an important channel of knowledge transfer, helping generate new knowledge and increasing rates of technological imitation.

2.4.4 Linkages between business and research sectors

A fairly large evidence base is emerging on the role of links between research and business communities in driving the returns to research investment. In general, we might expect that collaboration acts as a channel for knowledge exchange which could help the link between knowledge stocks and innovation, and thus increase the returns to R&D investments (or at least reduce lag times).

This is a topic that has been treated both from a macroeconomic perspective, using variables indicating engagement in traditional production function models, and a microeconomic perspective looking at individual academics and examples

[33] Note there is controversy over the robustness of this result: see Keller (1997).

of collaboration at the individual firm and university level. The role of geographic closeness between business and academics has also been emphasised.

Private and public collaboration from a macroeconomic perspective

Berman (1990) analyses the role of direct industry funding for research conducted in universities. He finds that industry funding is associated with additional industry-level R&D funding, and leads to marketable returns with a much shorter time lag (about 5 years) than for university research financed in other ways (about 12 years), though this could just reflect industry funding "nearer to market" research. Medda et al. (2003) use a sample of 1,008 Italian firms from 1992 to 1995 to analyse the effects of collaborations on productivity outcomes. They find that collaboration *between firms* was highly effective, resulting in more rapid productivity growth. However research conducted as collaborations *between firms and universities* had no impact on firm productivity. The authors caution that this may not be due to university research being unproductive; rather it could be that the types of projects conducted in collaboration between firms and universities may be further from market or otherwise less likely to generate commercial returns.

Private and public collaboration from a microeconomic perspective

Micro-level analysis of individual firms and academics has focused on two main types of university-industry relationships:

- **"commercialisation"** (or "technology transfer"); and
- **"academic engagement"**.

"Commercialisation" refers to the exploitation by businesses of an academic idea to generate financial rewards. For example, Technology Transfer Offices (TTOs) may be created with the specific objective of providing an intermediary platform bridging university and industry. Lockett and Wright (2005) find a positive correlation between the business development capabilities of UK TTOs and start-up formation, though Chapple et al. (2005) find TTOs at UK universities have low levels of absolute efficiency compared to US TTOs.

O'Shea et al. (2008) provide a review of the literature on the determinants and impacts of university "spin-off" activity. Shane (2004) finds spin-off companies to be 108 times more likely than the average new firm to go public and also to create more jobs than the average new business in the US. The US Association of University Technology Managers (2001) found that 69% of university spin-offs founded between 1980 and 2000 remained operational in 2001, again above the average survival rate of new firms. However, other studies have found less clear-cut results. Ensley and Hmieleski (2005) compare a sample of 102 high-technology university-based start-ups and a matched sample of 154 independent high-technology new ventures in the US. They find university-based firms to be significantly lower performing in terms of net cash flow and revenue growth. They suggest this could be due to differences in the composition and experience of management teams. Bonardo et al. (2011) perform a similar analysis matching 143 university-based firms that went public in the UK, Germany, France, and Italy during the period 1995 to 2002 to a sample of independent firms. At IPO stage, university-based firms have higher market values than comparable independent firms, consistent with university affiliation being viewed by investors as a credible signal of the quality of a firm. However, this does not appear to translate into longer-term success.

"Academic engagement" involves collaboration between the university and business sectors, often based on personal relations. A summary of some of the key literature looking at the degree of and motivations for this collaboration is given in **Table 16** in Appendix B. For example, D'Este and Perkmann (2011) identify three main forms of collaboration:

- "collaborative research": arrangements aimed at cooperation on R&D projects that are not directly commercially relevant;
- "contract research": referring to research that is directly commercially relevant, often explicitly commissioned by firms; and
- "consulting": research or advisory services generally provided by individual academic researchers.

Using survey data of UK researchers holding grants from the Engineering and Physical Sciences Research Council (EPSRC), they find 40 to 50% of academics report collaborative or contract research with business (defined as being engaged for at least one year in a two-year period). Fewer academics report any patenting activity (22%). The motivations for being active in a university-business link vary based on the type of activity: patenting appear to be motivated solely by the commercial exploitation of knowledge, while engagement is mainly motivated by research opportunities, including access to in-kind resources such as equipment or research expertise.

Several researchers have studied the characteristics of individual researchers and institutions involved in external engagement with business. Perhaps surprisingly, higher-quality institutions are on average less likely to collaborate (D'Este and Patel, 2007; Ponomariov, 2008; Ponomariov and Boardman, 2008), though other studies (Hughes et al., 2013) find that academics in high-rated institutions are more likely to engage in knowledge exchange with the private sector. There is also robust evidence that higher-quality individual academics (measured by scientific productivity) are more likely to collaborate (Bekkers and Bodas Freitas, 2008; Gulbrandsen and Smeby, 2005; Haeussler and Colyvas, 2011; Louis et al., 1989). This apparent inconsistency is perhaps reconciled if lower-quality institutions have smaller financial resources and so greater incentives to engage with the business sector for financial motivations, and if businesses seek out higher-quality individuals with whom to collaborate.

This literature has provided a considerable degree of evidence on whether and why academic researchers engage with business, but has said rather less about the success or otherwise of such interactions in terms of outcomes and economic returns. Our case study findings (see Section 4) make it clear that academic partnerships with key strategic industries like aerospace and life sciences are highly valued by businesses, recognising the key need to absorb scientific knowledge produced in academic institutions as a way to drive innovation, but also point to the conceptual difficulties of disentangling the returns to this collaboration from the returns to other investments needed to innovate.

2.4.5 Geographic closeness between firms and researchers

There is a body of literature that suggests that the proximity of firms to research centres influences the returns to research investments. This complements our case study evidence which suggest that physical proximity remains a key driver of collaboration, allowing for trusted relationships between academics and business partners to emerge over time, and for easier interaction to solve commercial problems drawing on academic and scientific expertise.

Adams and Jaffe (1996) use data from the US chemical industry from 1974 to 1988 and find that the productivity-enhancing effects of R&D are diminished as the distance between plant and research centre increases. They also find that increases in the 'technological distance' (the type of activity conducted by the research centre and the plant) also reduces the productivity-enhancing effects of R&D. Using data from 1982 across 43 US states, Anselin et al. (1997) find that spillover benefits from university research for firms in the private sector extend around 50 miles from the university, but that this is not driven by increases in private sector R&D for firms located nearer to universities.

In the UK, Simpson and Abramovsky (2009) draw on a range of data sources on business location and business R&D facilities, university research facilities and their quality and measures of interaction between firms and universities from survey data. They find evidence that R&D facilities in the pharmaceutical sector are likely to locate in the proximity of high-quality university chemistry departments, after controlling for the proportion of educated labour force (to degree-level or above) in the local population, the presence of manufacturing activity in that sector, and population density. Weaker evidence of co-location is found for R&D facilities in the chemicals sector, and no evidence for other industries such as vehicles and machinery (where co-location with *production* appears to be more important than proximity to universities). When innovative firms in the chemicals and vehicles sectors are in the vicinity of academic departments, they are more likely to co-operate or have informal exchanges of information with universities. Again, though, it is unclear what these location choices imply for the returns to business R&D.

2.5 Analysis of gaps in the literature

With regard to the framework set out in Section 1.2, the most significant gaps in the evidence base appear to relate to the following issues:

- The overwhelming majority of the evidence relates to private returns to private sector R&D investments by firms, and social returns generated through spillover effects at the industry, national and international levels. By contrast, there is relatively little evidence on the returns to non-R&D intangible investments, both private and social.
- None of the literature appears to have estimated the variation in rates of return to the capital and resource R&D investments either in the private or public sectors. Of course these may be difficult to disentangle are likely to exhibit a high degree of complementarity.
- In terms of public investment, there is a large body of evidence on comparing returns to private and public R&D spending, though this focuses primarily on R&D conducted by the private sector but which may be funded publicly or privately. Much less is known about the returns to publicly funded R&D of different types, including:[34]
    - The returns to public R&D investments delivered by different funding bodies (e.g. through universities, research councils or higher education);
    - The returns to public investment in basic or applied research.
- Little consistent evidence (other than occasional case studies) has said much about the returns to public R&D investments which accrue through forms other than their impact on private sector output or productivity. This includes, for example, the non-market benefits of public R&D investments in health, defence and departmental investments in policy development and public sector productivity.
- Although there is quite a large literature suggesting that, overall, public R&D investments do not crowd out private R&D investments (and may well leverage additional investment), there is a lack of evidence which draws on experimental methods to explore these issues, which would be useful to improve the robustness of the evidence.

[34] Our econometric analysis in Section 3 is designed to shed some light on these issues.

- There is little as yet compelling evidence on the role of wider influences on the returns. For example:
    - There is no evidence on whether macroeconomic conditions affect the returns to investment. Macroeconomic conditions could have indirect effects on the returns through their effect on the level of investment; they may have direct effects as well (for example, if in a recession private funding for R&D is reduced either because of financing constraints, there may be larger marginal returns to public investment).
    - There is little evidence on the influence of the regulatory environment or other institutional or corporate governance features which might affect the returns to knowledge investments. As noted by Hall (2011), there is some evidence that these sorts of features matter for the amount of investment and innovative activity in measurable ways, but it is not clear whether they affect the *returns* to investment.
    - There is quite a large literature on links between business and researchers exploring motivations for collaboration. At the moment the evidence is rather thin on whether such collaboration yields higher returns to investment.

More generally we have the following observations:

- Much of the evidence draws on firm-level data in manufacturing, both because data tend to be more easily available and because inputs and outputs in manufacturing are more easily measured and valued. However this calls into question the transferability of the results.
- Little evidence speaks to whether returns are constant over time. Production function methods tend to use all the observed variation across time and (where applicable) across country, firm or sector in order to estimate a rate of return, but given data constraints the models tend not to be able to look at whether this return is time-variant.
- Little evidence says much about the time profile of returns, and whether they decay quickly, slowly or not at all (in particular for publicly-funded investments).

3 Econometric analysis: the social returns to research council R&D investments

3.1 Introduction

Our literature review revealed relatively little evidence on the social returns to *different forms* of R&D investments made by the public sector.

The main exception was the work of Haskel and Wallis (2010, 2013) who found evidence of a statistically significant, positive correlation between publicly-financed R&D investments delivered through research councils and later productivity growth in private UK industry. This is evidence that research council R&D investments generate social returns through improvements in private sector productivity. Of course, as has been noted several times already, this does not imply that other forms of publicly-funded R&D investment have no social returns, but rather that these effects are harder to detect in the data used for these kinds of empirical studies. The value of other public investments (e.g. R&D spending by civil departments, defence or Higher Education), may instead be felt in other ways such as their impact on health, education, public sector productivity or national security. Alternatively, long lag times between basic scientific knowledge and the development of productivity-enhancing innovation in the private sector may mean current data sources (which have relatively short time series of data available) are insufficient to capture the returns adequately.

Using publicly-available data, we adopt and build on the Haskel and Wallis evidence by exploring whether there is variation across *types* of research council R&D investments in terms of their impact on private sector productivity. Specifically, we look at two breakdowns of research council expenditure which can be measured consistently:

1. The type of research council based on broad activity area;
2. The type of research in terms of Frascati (OECD, 2002) classification (basic, applied, experimental development).[35]

Our hypothesis is that private industry productivity is most likely to be increased as a result of research council R&D investments that are most similar to those which industry might itself conduct: those which are science-, engineering and technology-related, and investments in applied research.

[35] The Frascati Manual (OECD, 2002) is the standard way in which R&D is classified and defined in order to be consistently measured and collected across countries.

Broadly, our results bear this hypothesis out. We find:

- Evidence of a positive, significant social rate of return to research council spending in terms of later private sector productivity. The marginal rate of return appears to fall, though remains high, as we add further years of data to the analysis. Given the substantial increase in research council investments over time, this declining return indicates (as we might expect) decreasing marginal returns to additional investment, but still suggests that additional investments are likely to yield high social returns.

- Evidence that scientific and medical research generate the most consistently significant positive impact on private sector productivity, though all forms of research council spending (including non-scientific spending on social sciences and humanities) yield positive social returns.

- Evidence that the social returns to basic research funded by the research councils tends to be small (typically statistically insignificant), while the returns to applied and experimental development research tend to be larger, though our data may span too short a period to pick up the returns to basic research fully.

- That our results appear to be robust to a number of specification checks, including to the model specification, the lag structure and the inclusion of additional control variables.

Again, it is important to reiterate that our results do not suggest that non-scientific or basic research funded by the research councils has no economic returns, simply that we do not observe their impact after a relatively short lag on private sector productivity, the form of social return we are able to capture in our analysis. Were we able to measure public sector productivity reliably, we may expect an analysis of the impact of civil departmental R&D investments to show up there; similarly, were we able to measure the impact of basic R&D investments with a lag of 10 or 20 years we may expect to see larger effects on private sector productivity.

3.2 Methodology

We estimate a production function which relates changes in output (in this case productivity growth in the private sector) to lagged measures of public R&D investments as a proportion of value-added. Under some assumptions (described in Appendix A),[36] this approach should yield estimates of the social returns to these investments in terms of their additional impact on industry productivity.

Our main estimating equation takes the form:

$$\Delta \ln TFP_t = \rho \left(\frac{R^{PUB}}{Y}\right)_{t-N} + \alpha_1 Z_t + v_t$$

Where:

- $\Delta lnTFP_t$ is annual total factor productivity (TFP) growth in the market sector between year *t-1* and year *t*;[37]
- Y is market sector value-added;
- R^{PUB} is a measure of public sector R&D or components of it;
- *N* represents the number of lags;
- Z_t are other control variables that influence TFP growth in the market sector;
- v_t is an error term (assumed to be independently and identically distributed).

The main parameter of interest is ρ, the social rate of return to public R&D.[38]

We use time series data to construct the variables, and estimate the model using ordinary least squares (OLS) with standard errors which are robust to possible heteroskedasticity.

Including lagged public R&D reflects the fact that it can take time for investments to yield returns. We draw on the evidence from our literature review which suggests that lags between *private* R&D investments and returns from new innovation are in the order of around 2 years (Pakes and Schankerman, 1984) and use a 2-year lag as our basic specification. Of course, we also found evidence in the review that lags between *public* R&D and innovation were typically much longer than this; however, as noted above, our main focus in this work is on

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36 These include maintained assumptions of perfect competition and constant returns to scale which allow a TFP measure to be used as the dependent variable rather than an output measure. Given our short time series of data, our preferred approach is to minimise the number of control variables in the specification in order to maximise the number of degrees of freedom. Given that we are using aggregate, market sector data, maintaining an assumption of perfect competition and constant returns may reasonable.

37 TFP growth is a measure of the change in output once observed changes in inputs are accounted for. The 'market sector' excludes sectors for which outputs are difficult to measure, such as real estate, public administration and education, health and social services (O'Mahoney and Timmer, 2009).

38 More properly it will be the gross rate of return; if we are willing to assume that publicly funded knowledge stocks do not depreciate than it can also be interpreted as a net rate of return.

public R&D which is most similar to the sort of investments made by the private sector. We are also limited by the time series period of data available in the number of lags which we can include in the model. As described below, we experiment with a number of different specification checks using different lags.

3.3 Data

Our analysis is based largely on public data from a number of sources, which have been cleaned and compiled to be internally consistent.

3.3.1 Data sources

- **EU KLEMS:** an industry-level database of capital (K), labour (L), energy (E), materials (M) and service (S) inputs, outputs and productivity measures. The database contains data for 25 European countries, the US and Japan from 1970 onwards. The most recent release of UK data was in October 2012 which contains updated data to 2009.[39]

- **SET:** BIS publishes the Science (S), Engineering (E) and Technology (T) statistics (compiled by the ONS). The SET data include detailed information on the value of public R&D investments. We use the 2013 release, which contains data on a financial year basis between 1986-87 and 2012-13.[40]

- **BERD:** The ONS Business Enterprise Research and Development (BERD) data gives measures of private sector R&D. We use data from the November 2013 release, which includes industry-level R&D data on a calendar year basis between 1981 and 2012.[41]

- **ONS internet access data:** In our robustness checks we consider variables which might be correlated with private sector productivity, including internet penetration rates. We use calendar year level ONS data from *Internet Access: Households and Individuals* publication. Data are available only from 1998 onwards; rates are assumed to be zero in earlier years.[42]

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[39] EU KLEMS data can be found at http://www.euklems.net/.

[40] The data are available at https://www.gov.uk/government/publications/science-engineering-and-technology-statistics-2013. Note that the available data do not include a breakdown of public R&D spending into Frascati Manual types over the whole period; we are grateful to BIS for supplying this series in earlier years. The data supplied by BIS appear to be consistent with the published data in the periods where the two series overlaps.

[41] See http://www.ons.gov.uk/ons/rel/rdit1/bus-ent-res-and-dev/2012/rft-berd-2012.xls.

[42] See http://www.ons.gov.uk/ons/rel/rdit2/internet-access---households-and-individuals/2013/stb-ia-2013.html.

- **OECD:** We obtained data on productivity and government R&D investments in other G7 economies from the OECD statistics database.[43] These are used as control variables in our modelling, including the gap between the UK and US labour productivity (which reflects the capacity for the UK to 'catch up' to the productivity frontier, assumed to be the US, as a source of productivity growth) and foreign public R&D investments in other major economies (weighted by PPP per capita income) which could have wider spillover benefits to UK market sector productivity.

3.3.2 Specific variables and data processing

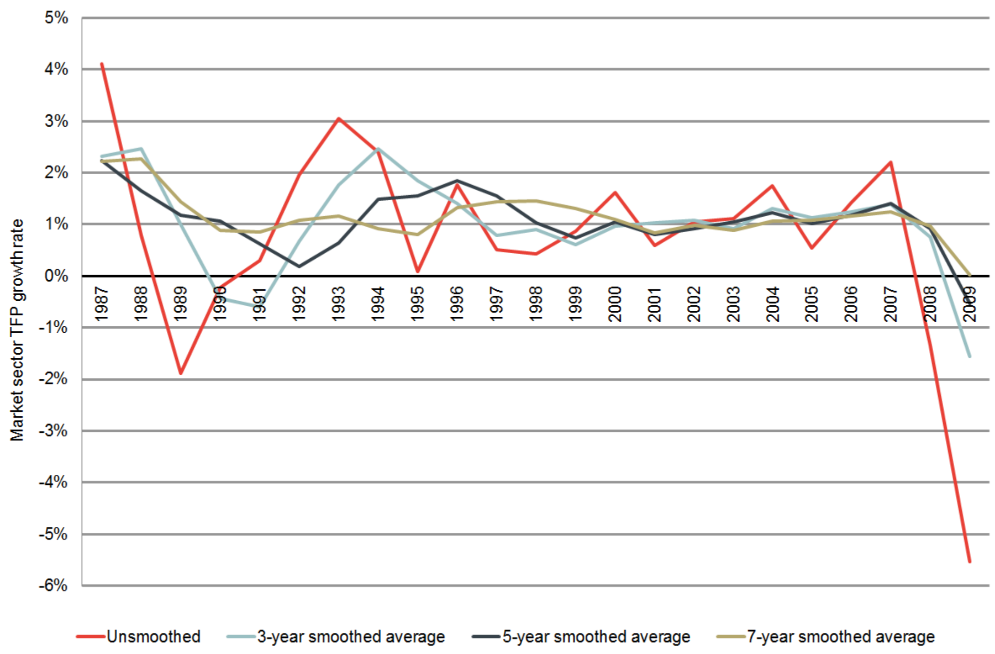
Productivity and value-added

We take EU KLEMS estimates of UK market sector value added and TFP. These data are available on an annual basis between 1972 and 2009.

The TFP data are presented as an index; we take the difference in the log of the index to obtain the annual growth rate, illustrated in **Figure 5** for the period 1987 to 2009 (the longest consistent period of data we can use for our analysis once we combine data from the various sources).

[43] See http://stats.oecd.org/

Figure 5. Market sector TFP growth rate, 1987 to 2009



Source: EU KLEMS, Frontier Economics

The annual data series is rather noisy. Studies of TFP growth commonly use a smoothed measure for analysis to remove some of the year-on-year noise and uncover more of the underlying trend in overall productivity growth (IMF, 2010). We show a number of smoothed series in **Figure 5**, calculated as simple rolling weighted averages of the most recent 3-, 5- and 7-year data periods.[44] Clearly the longer the period over which the series is smoothed, the smaller the variation in TFP growth we observe. We take the 3-year smoothed average as our baseline specification; we explore robustness of the results to other averages.

There is also a very striking, negative TFP growth measure for 2009. We return to this in our discussion of the data period for analysis below.

Public R&D

The SET data contains breakdowns of public R&D spending which we exploit for our analysis. The key breakdowns are shown in **Table 4**.

[44] Note that Haskel and Wallis (2013) use a different smoothing approach. They take a weighted average of TFP growth in the current year, the previous year and the subsequent year, assigning a 50% weight to the current year and 25% each to the adjacent years. Note that in their results, they find consistent evidence that one-year lags of research council R&D are positively related to market sector TFP growth whereas we find more consistent results using a two-year lag; this could partly reflect this different smoothing mechanism (Haskel and Wallis use some of year *t+1* productivity growth in their dependent variable whereas we include some of year *t-2*).

Table 4. Split of Public R&D investments in SET data

By source
Research councils
Higher education funding councils
Civil departments
Defence
UK contribution to EU R&D budget
By type
Basic
Applied – strategic
Applied – specific
Experimental development

Source: SET Statistics 2013

We now give more detail about the construction of these breakdowns for our analysis.

Public R&D by source

The SET data contain detailed information on spending across different sources.[45] To ensure the data are as comparable as possible across time, we make a number of adjustments to the published statistics. In particular, we:

- include spending by the Office of Science and Technology as a departmental spend rather than a Research Council spend;[46]
- exclude data on NHS R&D spending from civil departmental public R&D since this information is only available from 1996 onwards;

45 As noted earlier, there is of course a large degree of complementarity of different forms of public R&D investments, such as the fact that much research council funding goes to higher education institutions (Hughes et al., 2013).

46 The OST was a non-ministerial department which, until 2007, was responsible for science and technology policy and distributing money to the research councils. It was absorbed into DIUS in 2007.

  - exclude the "pensions/other" category from the Research Council spend from 1994-95 when the data are separated (prior to then, research council pension needs were met centrally).

Trends in nominal public R&D spend by source are shown in **Figure 6**. The striking growth in research council spending since the early 2000s is clearly evident, as is a significant fall in defence R&D spending. R&D spending by civil departments fell in the early 2000s but then rose again later in the decade. Funding for higher education R&D also rose rapidly though began to decline in the early 2010s (though this period will not be captured in our analysis).

We further decompose the research council figure according to the broad type of research that the council funds. Research councils have been re-organised over time so it is not possible to look over the whole period at a consistent measure for individual councils. Instead, we group the spending into broad activity headings and allocate the different research council spending accordingly.[47]

We define four groups of research council investments as follows:

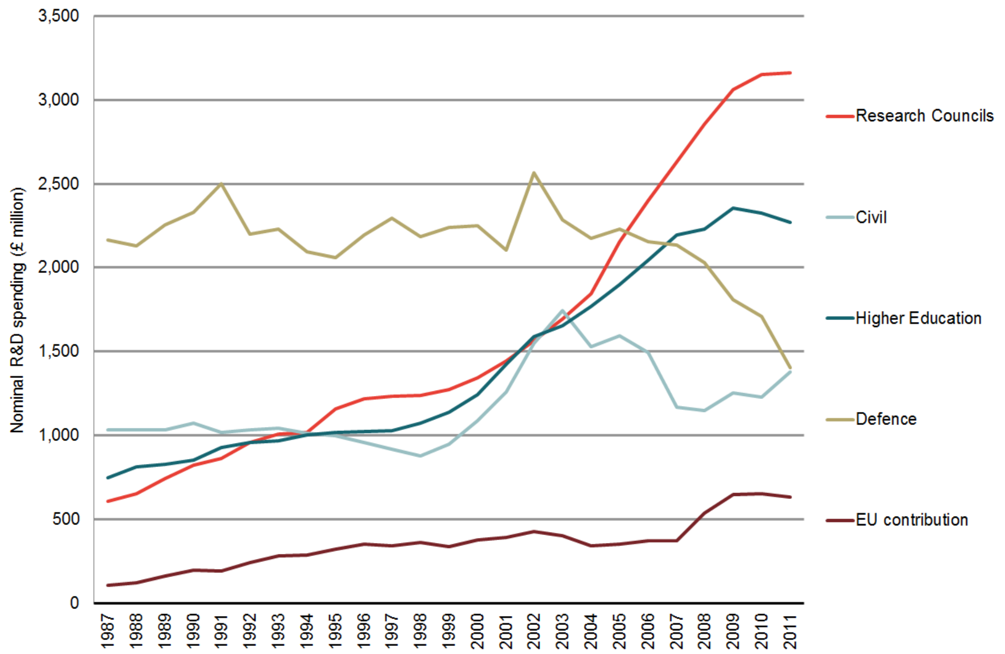
- **Non-science spending** (social sciences, arts and humanities)
  - Economic and Social Research Council (ESRC)
  - Arts and Humanities Research Council (AHRC)
- **Medical science**
  - Medical Research Council (MRC)
- **Physics, astronomics and engineering**
  - Science and Engineering Research Council (SERC)
  - Engineering and Physical Sciences Research Council (EPSRC)
  - Particle Physics and Astronomics Research Council (PPARC)
  - Council for the Central Laboratory of the Research Councils (CCLRC)
  - Science and Technology Facilities Council (STFC)
- **Other science**
  - Agriculture and Food Research Council (AFRC)
  - Natural Environment Research Council (NERC)
  - Biotechnology and Biological Sciences Research Council (BBRSC)

The main tension in this division is the formation of the BBSRC in 1994 (included as 'other science') from part of the activities of the AFRC and SERC, since the latter is included in the 'physics, astronomics and engineering' category. This is likely to see a small inconsistency with some of the 'other science' funding

[47] We are grateful to James Archur from BIS for advice on this classification and a similar attempt to categorise departmental expenditures into broader groups.

from the SERC having previously been allocated to the 'physics' group. Since we have no clear way to split individual research council spending in each year across these broad headings we allocate each council in each year to a single group, and this division appears to be the most sensible.

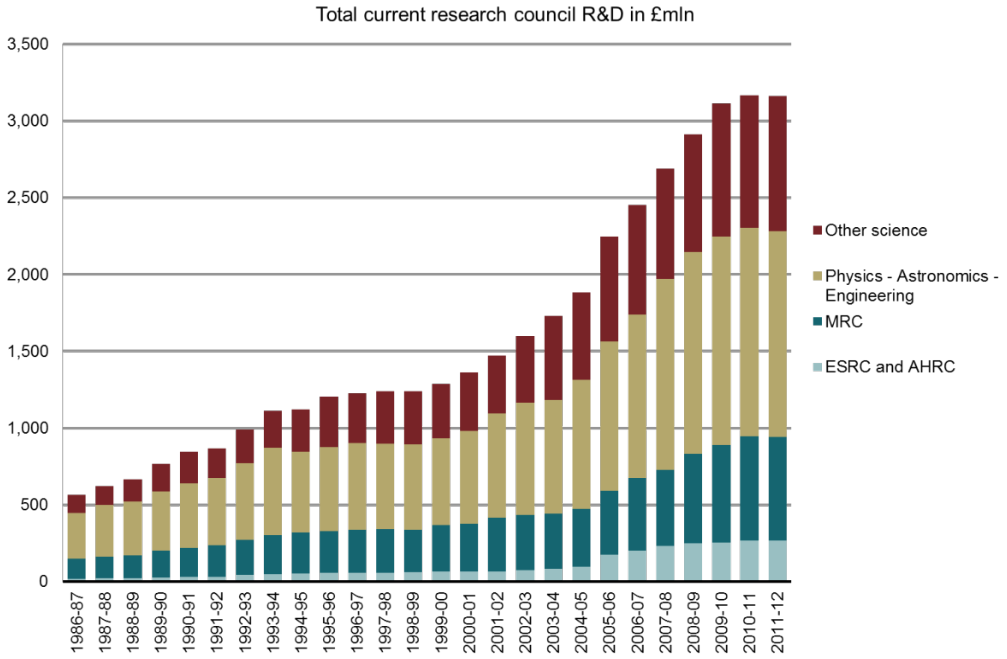
Figure 6. Publicly-funded R&D expenditure by source



Source: SET Statistics 2013, Frontier Economics

Figure 7 shows nominal research council spending by category over time. Spending has clearly been growing for all categories, though not at the same rate such that the composition of the overall research council has changed over time. Comparing 1994-95 (given the slight inconsistency in the categories noted above) to the most recent year 2011-12, for example, we find that the most significant changes are the share of total research council spending for non-science (ESRC and AHRC) has increased from 4.9% to 8.5% whereas the share for Physics, Astronomics and Engineering has fallen from 45.3% to 42.4%. Note, though, that in cash terms the non-science spending is still much lower than any of the science-based categories.

Figure 7. Public Investment in Research Councils over time



Source: SET Statistics 2013, Frontier Economics

Public R&D by type

We are able to disentangle public R&D investments made by research councils, civil departments and defence into three broad types based on the Frascati Manual definitions:

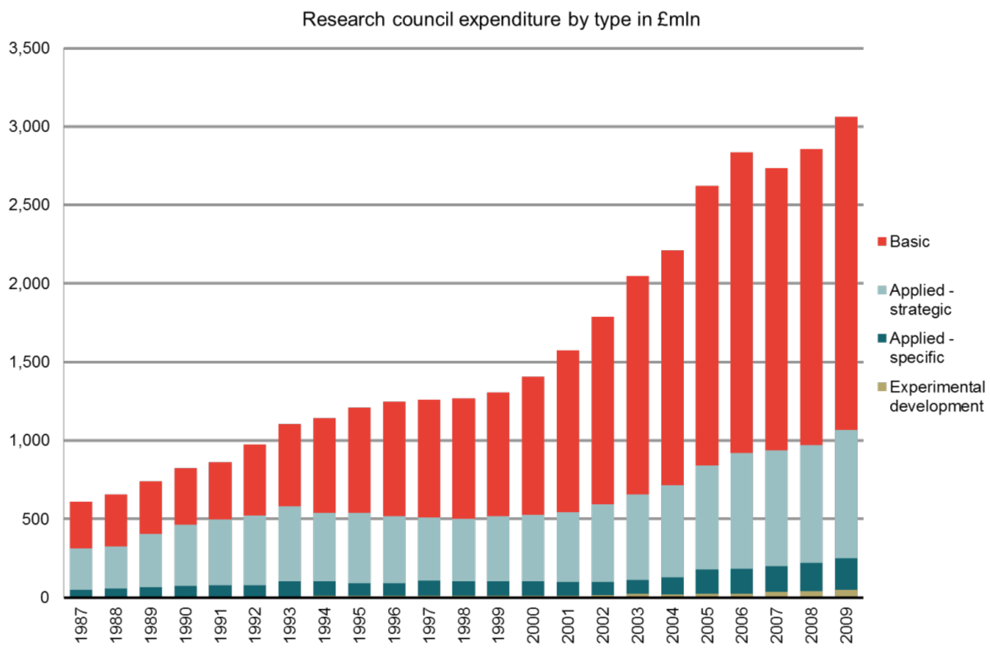
- **Basic research –** defined as experimental or theoretical work designed to acquire new knowledge, but without particular applications in mind.
- **Applied research** – defined as work to acquire new knowledge which is directed primarily towards specific practical objectives.
- **Experimental development –** defined as systematic work building on existing knowledge directed at producing new product or process innovations.

These definitions broadly cover, in order, research according to "closeness to market". The lags between basic research and TFP growth, therefore, would be expected to be longer than applied research, and longer again than experimental development.

The applied research figures are also further divided into *strategic* and *specific* spending. Strategic spending is applied spending without a specific application in mind, whereas specific spending is focused on a particular application. Strategic applied spending is probably less close to market than specific applied.

For research councils, the breakdown of spending across the three main headings is shown in **Figure 8**.

Figure 8. Research Council expenditure by type



Source: SET Statistics 2013, Frontier Economics

There has been particularly rapid growth in basic research since the mid-1990s, and very little experimental development research, though this has begun to increase in the most recent years. Research councils do invest significant amounts in applied research as well.

Private R&D investments

We include lagged private R&D investments in the market sector in our baseline specification. The EU KLEMS TFP measure is based on output growth rates net of changes in labour and physical capital, but does not account for any changes in intangible capital inputs such as R&D. As a result, if public and private R&D investments are correlated, by excluding private R&D from the specification we could wrongly attribute some of the productivity impact of private R&D to public R&D, leading to an omitted variable bias.

Our market sector R&D measure is obtained from the ONS BERD survey. The survey provides a measure of total private sector R&D on a calendar year basis, which is then decomposed at an industry level. To define 'market sector' private

R&D, we exclude "public administration" R&D spending. We also exclude R&D devoted to "computer programming and information service activities". The EU KLEMS TFP measure we use already accounts for ICT capital (which includes software) and there is a risk of double counting if this expenditure is included in the private R&D measure since much R&D in the computer services industry is writing of software.

The resulting private R&D measure is highly positively correlated with total public R&D as shown in **Figure 9**; this suggests a possible risk of omitted variable bias should we exclude it, but also gives rise to multicollinearity problems should we include both private and public R&D measures in the same specification. Our preferred approach is to control for private R&D to ameliorate the risk of omitted variable bias. It is important to note that the inclusion of private R&D in the model specification serves to control for this expenditure, rather than as a way to measure the (private) returns to private R&D explicitly.[48]

Additional control variables

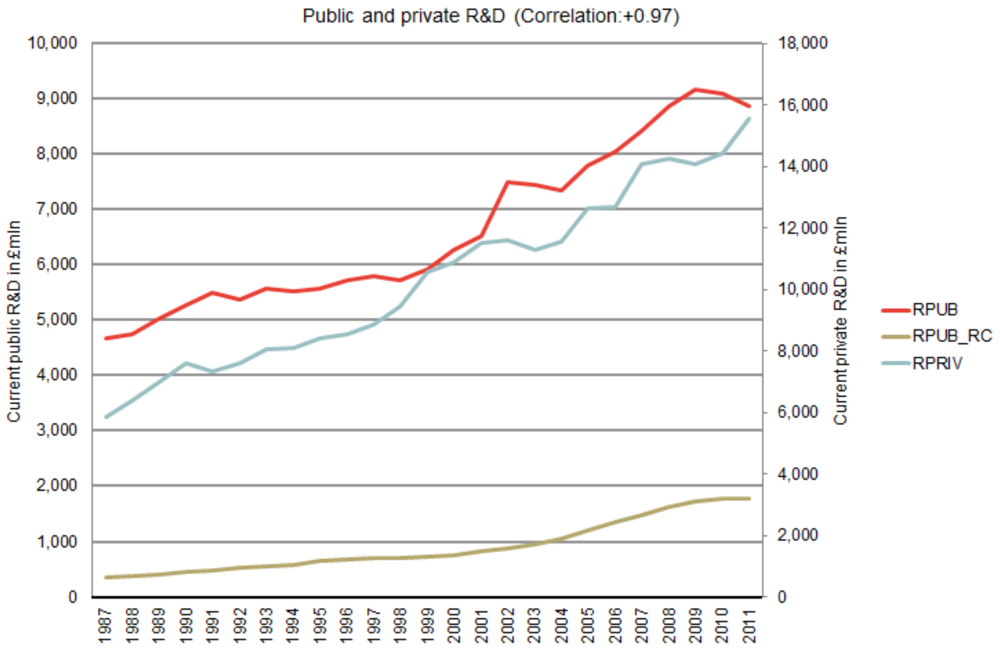
Other covariates we can include in the model are the internet penetration rate, the US-UK productivity frontier and foreign government public R&D.

Internet penetration rates

The extent to which households and firms are connected to the internet may be expected to affect productivity growth if this technological development allowed firms to conduct their business more efficiently (Haskel and Wallis, 2010 and 2013). We obtain the household-level internet penetration rate from ONS, though data exist only from 1998 onwards. We assume the rate is zero in earlier years.

[48] In order to measure the returns to private R&D expenditure explicitly we would need to take account of the fact that private R&D expenditure is likely to depreciate over time. This would mean that we should include the change in the stock of private R&D as well as the private R&D expenditure for that period. For our present purpose of estimating the social returns to public R&D, we include the flow measure purely as a control.

Figure 9. Correlation between public and private R&D investments



Source: BIS-SETS, BERD, Frontier Economics. Note RPUB = public R&D investments (total), RPUB_RC = research council investments and RPRIV = private R&D investments.

The US/UK productivity frontier

Relative labour productivity between the US and UK could affect UK market sector productivity if it proxies the extent to which the UK is below the productivity frontier, assumed to be represented by the US (Haskel and Wallis, 2010 and 2013). We define the measure as the log of the ratio between average labour productivity (GDP per hour worked) in the two countries. GDP per hour worked data were obtained from the OECD.

Foreign government public R&D expenditure

Foreign government public R&D expenditure could affect UK market sector productivity through international spillover effects. We obtain data on public R&D (GovERD) from the other G7 countries (Germany, France, Italy, the US, Canada and Japan) from the SET Statistics, and weight each public R&D expenditure by the specific GDP of that country relative to the UK GDP. We then added all the weighted foreign R&D expenditures to arrive at total foreign government public R&D expenditure.

Timing adjustments

All of our sources provided data per calendar year (1 January – 31 December), apart from the SET statistics where data are presented per fiscal year (1 April – 31 March). In order to make the two consistent we assume that the SET statistics are uniformly allocated throughout the year, allowing us to express them on a calendar year basis (for example, the 1992 variable is constructed as ¼ of the 1991-2 value plus ¾ of the 1992-93 value).

3.4 Caveats and robustness checking

There are a few key caveats for this analysis:

- **Sample size –** our analysis can make use of, at most, 23 observations (the overlap between the EU KLEMS and SET data, from 1987 to 2009). This may make it very hard to pick up statistically significant effects, even when the impacts are genuine (i.e. we may be unlikely to reject a false null hypothesis of no correlation). In addition, we find that the 2009 TFP observation is problematic (see **Figure 12**) and so exclude it from our analysis; this reduces our sample size further.

- **Deflation –** The financial variables in our model are expressed as ratios (e.g. R&D investments relative to value added). So long as both numerator and denominator are deflated by a common price index, the ratio is not affected whether we express variables in cash or real terms. However, it is not necessarily clear this is appropriate – the costs of conducting R&D need not rise in line with economy-wide inflation, for example. The aim of a public or private R&D measure in the specification is to capture something about the quantity of R&D being carried out in the economy. We observe data on R&D *expenditure*. If the cost of R&D grows more rapidly than average prices, then increases in the ratio of R&D spending to value added may simply reflect the increased relative price of R&D services. There is little clear evidence on this issue, though efforts to construct separate deflators for R&D services in the US have not suggested any systematic difference between the costs of R&D and general inflation.[49] Therefore we proceed to use the non-deflated ratios in our analysis.

- **Non-R&D intangible investments** – Although we control for private sector R&D, we do not include any measure of non-R&D intangible investments such as design or firm-specific human capital investment in our model, since there is no consistent data source providing this information over the time period required. This could lead to an omitted variable bias if this investment has a significant independent impact on market sector productivity and is correlated with public R&D investment.

[49] See for example, the paper by the American Bureau of Economic Analysis: 'Industry-level output price indexes for R&D; an input-cost approach with R&D productivity adjustment' (http://www.bea.gov/papers/pdf/industry_level_output_price_indexes_for_r_and_d.pdf)

We conduct a number of robustness checks of our baseline results:

- **Control variables –** we assess whether including or excluding the additional control variables (the UK/US labour productivity ratio, internet penetration ratio and foreign government R&D spending) outlined above has any impact on our results.

- **Lag structure –** as noted above, our baseline specification includes 2-year lags of private and public R&D investments. We assess whether changing the number of years with which R&D measures are lagged affects the key conclusions, using lags varying between 1 and 3 years. Longer lags are not plausible given the short time series of data we have available.

- **Smoothing structure** – our baseline approach uses the 3-year smoothed TFP growth measure as the dependent variable as outlined above. We experiment with a range of alternative smoothing approaches.

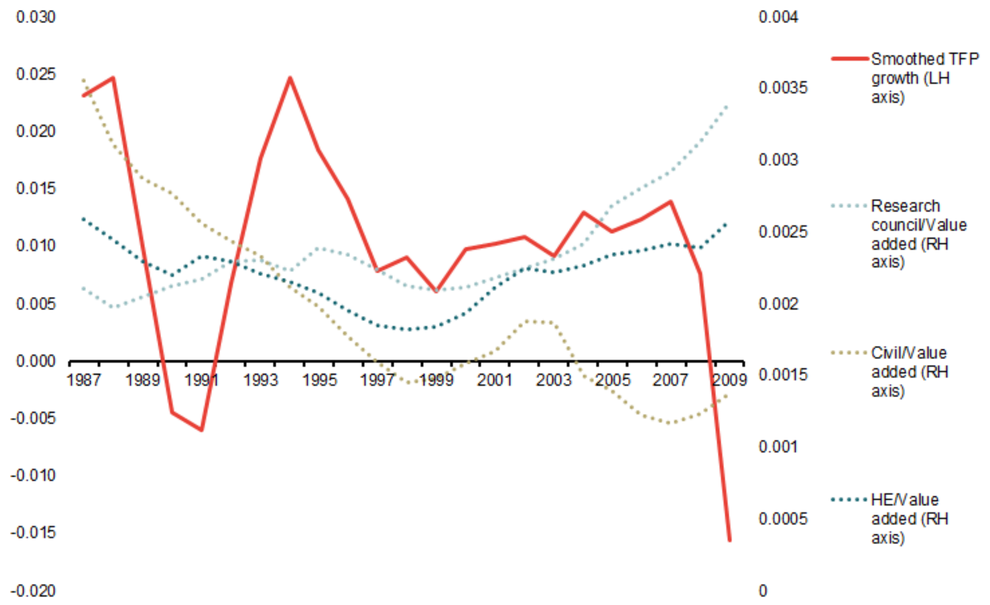
- **Data source –** to assess whether the omission of non-R&D intangible investment from our analysis has any effect on the results, we use alternative TFP data from Haskel and Wallis (2013) who revise the EU KLEMS variable based on detailed empirical estimates of other intangible investments by the market sector over the period.

Broadly speaking, we find little evidence that these robustness checks affect the main results in any qualitative way. As a result we focus on the baseline results and decompositions in the main text. The key robustness checks are reported in Appendix C.

3.5 Descriptive statistics

Figure 10 shows a simple plot of the main data: the three-year smoothed market sector TFP growth measure, plotted against the left hand side axis, and three forms of public R&D (research councils, civil departmental spending and HE) relative to market sector value added, each plotted against the right hand side axis. What is striking about the public R&D series is that they show quite markedly different trends over time, with research council investments rising quite substantially after around 2000, HE investments roughly flat over most of the period and civil investments falling quite consistently. The TFP series exhibits substantial variation (even when smoothed), with a large fall in TFP in the early 1990s recession which quickly recovers, a period of quite consistent TFP growth of around 1% per year which then fell dramatically at the start of the recent recession. This is consistent with ongoing interest in the UK "productivity puzzle" whereby the recession saw very large falls in output but commensurately small falls in employment.[50]

Figure 10. Time series plot of TFP growth and public R&D measures

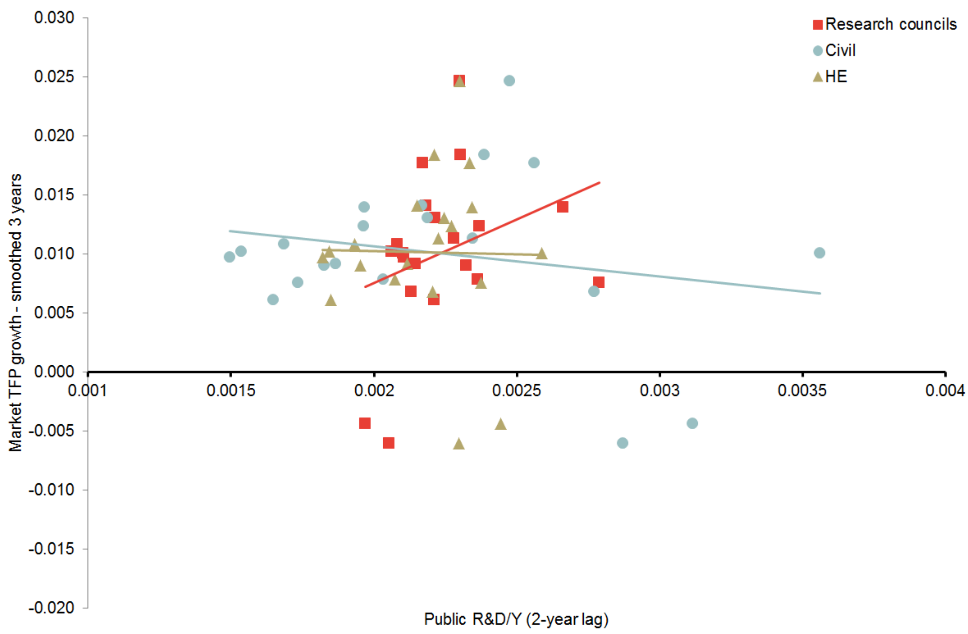


Source: Frontier Economics

How do these public investments relate to TFP growth? **Figure 11** below plots the TFP measure against two year lags of each of the public R&D input measures. We first plot data from 1988 to 2004, matching the data period used by Haskel and Wallis (2010). Linear best fits are shown for each public R&D measure. Strikingly, the results are similar to those in Haskel and Wallis (2010): a very strong positive correlation between lagged research council investments and TFP growth, and little correlation (even a slightly negative correlation) for other public R&D investments.

50 See for example Disney, R. et al. (2013), 'The productivity puzzles', in IFS Green Budget 2013 (http://www.ifs.org.uk/publications/6560)

Figure 11. Smoothed TFP growth against 2-year lagged public R&D investments, 1988 to 2004



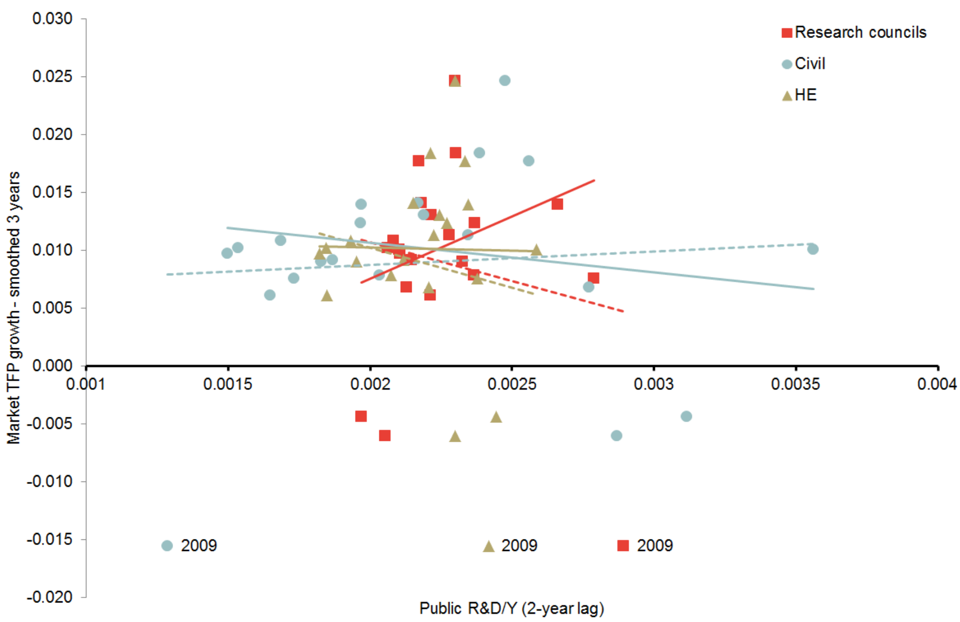
Source: Frontier Economics. Note: solid lines are best fit lines.

What if we now extend the data series to 2009? The results look very different as shown in **Figure 12**. The solid best fit lines are, as before, those based on data to 2004 whilst the dotted best fit lines are those based on data to 2009. The correlation over the extended period is slightly negative for research council spending, and if anything slightly positive for civil spending.

The key driver of this is the 2009 figure, as highlighted in the diagram. Smoothed TFP growth was around -1.5% that year, well below any figure previously recorded in the series. This large negative measure of TFP growth was associated with a very high figure for research council R&D spending relative to value added, and a comparatively low figure for civil R&D spending relative to value added (see the highlighted points on the plot). This single point therefore dominates the overall correlations.

There is a clear issue as to whether such an outlier should be included in the analysis. We do not include it, not just because the 2009 TFP growth figure is clearly so different from the rest of the data, but also because there is considerable uncertainty about the reliability of the productivity estimates during the great recession and how the "productivity puzzle" can be explained. One possibility is that labour and capital utilisation rates have fallen markedly (a form of hoarding) and this is not being picked up properly in the data, leading to an underestimate of the fall in input volume and so an overestimate of the decline in productivity. However until the data point is understood better, our view is that it should not be included given how much it impacts the results.

Figure 12. Smoothed TFP growth against 2-year lagged public R&D investments, 1988 to 2009



Source: Frontier Economics. Note: dotted best fit lines are based on data up to 2009, solid lines on data up to 2004

3.6 Results

The results of our main analysis can be found in **Table 5** to **Table 10**.

3.6.1 Social return to public investment by broad type of spending

We begin in **Table 5** by replicating, as far as we are able, the main specification run by Haskel and Wallis (2013). We use data to 2008 to relate smoothed TFP growth to measures of total lagged public R&D investments relative to market sector value added (column 1), taking the two year lag as our baseline as described earlier. We then decompose this into the broad type of public investment (column 2), entering each component together into a single regression. We then isolate the EU contribution (column 3), the research council investment (column 4), the civil expenditure (column 5), the higher education expenditure (column 6) and the defence expenditure (column 7), as concerns about collinearity and a limited number of degrees of freedom may make it difficult to identify the influence of each type of spending if combined in a single specification. Columns (1) – (7) employ the full data from 1987 to 2008.

Table 5. Baseline results – social returns by type of public R&D

Regression	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	
Constant	0.0260 (0.0153)	-0.0858* (0.0447)	0.00553 (0.0161)	-0.0138 (0.0319)	0.0197 (0.0145)	0.0213 (0.0209)	0.0157 (0.0224)	
Public R&D expenditure	0.283 (0.933)							
EU contribution		61.18** (24.47)	23.78 (15.97)					
Research councils		-5.258 (12.38)		10.71 (9.472)				
Civil expenditure		-16.36 (10.52)			-1.802 (2.801)			
Higher education		48.44** (22.27)				2.106 (5.146)		
Defence		2.459 (2.719)					-0.862 (2.192)	
Private R&D expenditure	-1.113 (1.063)	-0.324 (1.955)	-0.478 (0.927)	-0.00667 (1.085)	-0.328 (0.926)	-0.916 (0.983)	-0.103 (1.753)	
Research councils (to 2004)								39.47* (19.45)
Research councils (to 2005)								38.98* (18.92)
Research councils (to 2006)								36.75* (17.48)
Research councils (to 2007)								22.25* (11.98)
Research councils (to 2008)								10.71 (9.472)
Observations	20	20	20	20	20	20	20	
R-squared	0.038	0.417	0.140	0.098	0.045	0.040	0.041	

Source: Frontier Economics

Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

Finally, column (8) repeats the analysis in column (4) for research councils, but showing the importance of the period of data analysed by varying the end year of the analysis. Hence column (8) shows the research council coefficient from a sequence of regressions (following the specification in column (4)) each with different end dates.

Despite the fact that we use different data, we find qualitatively very similar results to Haskel and Wallis (2013). The returns to research council R&D investments are large, positive and declining over time as we add more years of data to the sample. At least until 2007, the coefficients are significant at the 10% level. When we use the sample up to 2008 the significance disappears, but the size of the coefficient remains positive and large.

Note that if we enter the components of public R&D in a single specification, the sign and significance is quite different as compared to entering them singly. This suggests strongly that collinearity and degrees of freedom issues may be affecting our ability to identify these separate effects independently. We therefore prefer to focus on the equations which enter each type of investment one by one.

In **Table 6**, we look at how the coefficient on the other forms of public investment changes as the sample period changes, replicating the analysis for research councils shown in column (8) of **Table 5**.

There is evidence of a large, significant social return to the UK contribution to the EU research budget, though again this diminishes over time and becomes insignificant more quickly than the research council figure. However, because of uncertainties over how that measure is constructed, we do not pursue a more detailed analysis of this finding further.[51]

The coefficient for higher education is also positive in all years, and declines over time, but is not statistically significant in any sample period. The coefficients for civil and defence spending are negative, but not statistically significant.

The most consistent evidence therefore suggests that research council R&D investments yield large, significant social returns through their impact on private sector productivity, as found by Haskel and Wallis (2010, 2013) and confirmed by our analysis. Again, this is despite the fact that we use different data (we rely entirely on publicly-available TFP and value-added measures) and different modelling approaches (smoothing and lag structure). Our findings on research councils are robust to a number of specification checks (we describe the robustness checking further in Section 3.7), including using TFP data which account for intangible investments, the lag structure, the smoothing mechanism applied to the TFP variable and the inclusion of additional control variables.

Again, it is important to re-iterate that our finding of a large, significant social rate of return to research council investments should not be taken to imply that public R&D investments delivered through Higher Education or departmental expenditures have no economic value. Rather, we are unable to find strong evidence that these investments have short-run impacts on private sector productivity. Given the limited time-series of data which are available, we are

[51] Data on the UK's R&D EU contribution are estimated, taking a proportion of the UK's overall net EU contribution that is assumed to go to R&D.

unable to look for longer-term impacts, and nor can we pick up some of the other ways in which these investments could yield social returns such as the effect on health, national security or public sector productivity.

Table 6. Baseline results – social returns by type of R&D and sample period

Regression	(1)	(2)	(3)	(4)	(5)
Effect of public R&D expenditure on	**Research councils**	**EU Contribution**	**Civil**	**Higher education**	**Defence**
Sample up to 2004	39.47* (19.45)	61.74** (26.54)	-2.395 (5.393)	13.31 (11.15)	-0.552 (2.425)
Sample up to 2005	38.98* (18.92)	47.23* (24.84)	-1.761 (2.844)	7.269 (7.714)	-0.626 (2.320)
Sample up to 2006	36.75* (17.48)	29.53 (20.39)	-1.604 (2.743)	5.219 (5.945)	-0.631 (2.277)
Sample up to 2007	22.25* (11.98)	22.36 (17.87)	-1.362 (2.751)	5.383 (5.078)	-0.749 (2.251)
Sample up to 2008	10.71 (9.472)	23.78 (15.97)	-1.802 (2.801)	2.106 (5.146)	-0.862 (2.192)

Source: Frontier Economics. Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

We now assess whether there is any evidence on how this impact breaks down by more disaggregate measures of the investment.

3.6.2 Social returns by research council area of activity

Table 7 decomposes total research council investments into the four areas set out in Section 3.3.2 (non-science; medical; physics, astronomics and engineering; other science). We follow the same approach as above: our baseline specification uses data up to 2008, and controls for private sector R&D. Column (1) simply mimics the overall research council result (column (4) of **Table 5**) as a point of reference. Column (2) enters each type of research council in a single specification; again, collinearity and degrees of freedom issues lead us to prefer entering them singly which we do in columns (3) to (6).

Table 7. Social returns by type of Research Council (data to 2008)

Regression	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP
Constant	-0.0138 (0.0319)	-0.0114 (0.0673)	0.0168 (0.0198)	-0.0334 (0.0237)	-0.0000 (0.0174)	0.00746 (0.0333)
Research councils	10.71 (9.472)					
ESRC and AHRC		-63.31 (76.06)	18.87 (42.05)			
MRC		-79.72 (58.32)		100.6** (40.83)		
Physics & Engineering		21.95 (25.39)			27.08 (15.86)	
Other science research		-3.072 (49.77)				10.24 (20.96)
Private R&D expenditure	-0.00667 (1.085)	-1.922 (2.705)	-0.508 (1.104)	-0.405 (0.880)	-1.088 (1.094)	-0.195 (1.398)
Observations	20	20	20	20	20	20
R-squared	0.098	0.323	0.042	0.286	0.172	0.043

Source: Frontier Economics Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

The coefficients suggest large, positive social returns to investments from each type of research council investment. Again the small sample sizes make it hard to pick up significant effects, though we find a statistically significant return to medical research investments.

To see whether we see the pattern of declining marginal returns for each type of research council investment that we saw for overall research council spending, we repeat the analyses in columns (3) to (6) for different sample periods, shown in **Table 8**. Again, these tables report the coefficient on the research council variable from a regression model run for a particular sample period, which includes that research council's investment in isolation and also controls for private R&D spending.

We see declining returns to each type of investment, though the decline is somewhat more marked for some forms of investment (e.g. non-science) than others (medical research). The non-science results are the most strikingly different, with a very rapid decline in the apparent return using data to 2007 compared to 2006. However it is worth noting the relatively small part of total research council R&D going to this non-science category (notwithstanding the relative increase in the share over time). It does appear, though, that the most consistent and robust positive effects on future private sector TFP growth come from medical and physics/engineering-based research councils.

Table 8. Returns by research council type and sample period

Regression	(1)	(2)	(3)	(4)	(5)
Effect of	**ESRC & AHRC**	**Science**	**MRC**	**Phys&Eng**	**Other Science**
Sample up to 2004	454.2** (174.0)	30.35** (11.81)	119.1** (43.50)	49.62** (18.77)	45.81 (59.10)
Sample up to 2005	433.3** (171.0)	30.22** (11.68)	114.0** (42.66)	49.30** (18.74)	39.77 (52.72)
Sample up to 2006	432.6** (169.1)	29.49** (11.21)	108.2** (42.13)	46.89** (17.96)	35.58 (46.71)
Sample up to 2007	105.1 (73.28)	24.09** (9.276)	107.8** (42.14)	41.38** (15.60)	23.47 (22.28)
Sample up to 2008	18.87 (42.05)	15.95 (9.192)	100.6** (40.83)	27.08 (15.86)	10.24 (20.96)

Source: Frontier Economics. Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

3.6.3 Social returns by research council Frascati category

In **Table 9** we explore the difference by type of research spending by research councils using the Frascati definitions set out above. We first enter the types (basic, applied strategic, applied specific, experimental development) together (column 2), then aggregating the applied research (column 3) and then entering each type separately (columns 4 to 8). Again, these baseline results control for private sector R&D and use the period to 2008.

Interestingly, we find smaller social returns for “far from market” public R&D than “near to market”: the returns are larger for applied and experimental development work than for basic research, and larger for specific applied than strategic applied research. Applied (particularly applied strategic) research appears to show the most statistically significant effect.

Table 9. Returns by research council Frascati activity

Regression	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep. variable	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP
Constant	-0.0138 (0.0319)	0.0298 (0.0419)	0.0170 (0.0404)	0.0265 (0.0291)	0.0240 (0.0169)	0.0257 (0.0168)	0.0208 (0.0170)	-0.0214 (0.0384)
Research Councils	10.71 (9.472)							
Basic		-4.171 (6.506)	-4.609 (6.502)	-0.467 (5.095)				
Applied - total			20.93* (11.62)		22.86* (10.95)			
Applied - strategic		34.93* (18.88)				27.99** (12.82)		
Applied - specific		-58.89 (63.61)					54.58 (46.14)	
Experimental development		207.4 (412.4)	299.9 (398.1)					446.5 (376.7)
Private R&D expenditure	-0.00667 (1.085)	-2.143 (2.437)	-1.530 (2.423)	-0.915 (1.413)	-2.144 (1.312)	-2.273 (1.312)	-1.144 (1.148)	1.414 (1.946)
Observations	20	20	20	20	20	20	20	20
R-squared	0.090	0.317	0.273	0.037	0.242	0.268	0.076	0.106

Source: Frontier Economics

Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

In **Table 10** we repeat the analyses of column (4) to (8) for different data periods. Again we see some evidence of declining marginal social returns over time, though not consistently: for example, the social returns to experimental development research appear to rise again in later sample periods. However it is worth being clear on the large standard errors around these estimates, so this could simply be driven by imprecision (in particular given the very small amount of money spent by research councils on experimental development research).[52]

The social returns to applied (in particular applied-strategic) research council expenditure are consistently significant over the time period considered. Returns to other types of research council expenditure also tend to be positive, but not always significant, possibly due to the sample size.

52 In 2011 research council basic research spend was around £1.9 billion compared to £1.2 billion on applied research and only around £53 million on experimental development research.

These results could reflect the lag structure, since we would expect basic research to require substantially longer than 2 years in order to become commercially useful in the market sector. Given the short time series of data, we are unable to test this effect using very long lags. As described in Section 3.7, we conduct a number of robustness and specification checks to these results, though given the sample period we are not reliably able to include more than three lags. We do not find any particular difference in the results for basic research using three lags, though again this is probably not long enough for that research to have an impact on private sector productivity.

Table 10. Returns by research council Frascati activity and sample period

Regression	(1)	(2)	(3)	(4)	(5)
Effect of	**Basic**	**Applied**	**Applied Strategic**	**Applied Specific**	**Exp Dev**
Sample up to 2004	2.389 (12.11)	31.10** (11.39)	37.08** (13.19)	94.44 (61.77)	493.5 (505.1)
Sample up to 2005	0.937 (9.530)	30.78** (11.28)	36.07** (12.98)	90.71 (60.20)	399.4 (421.7)
Sample up to 2006	0.681 (8.535)	29.86** (10.99)	34.83** (12.66)	90.41 (59.14)	398.4 (419.3)
Sample up to 2007	2.007 (5.024)	29.00** (10.42)	34.37** (12.24)	82.29* (46.66)	403.6 (393.3)
Sample up to 2008	-0.467 (5.095)	22.86* (10.95)	27.99** (12.82)	54.58 (46.14)	446.5 (376.7)

Source: Frontier Economics

Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The dependent variable is a simple 3-year smoothed moving average of TFP growth.

3.6.4 Interpretation of coefficients

So far, while we have commented on the sign and significance of the coefficient estimates which correlate different types of public R&D investment with later market sector TFP growth, we have not said too much trying to interpret the values as social rates of return.

In principle, as described, the method we adopt should allow us to interpret the coefficients *directly* as social returns to the various public R&D measures.[53]

[53] This, of course, relies on a number of strong assumptions, including constant returns to scale and perfect competition (which allow us to use TFP growth rather than output growth as the dependent variable, see Appendix A). However at the aggregate economy level, these may not be too restrictive, at least to a first approximation.

However the value of the coefficients would suggest extremely high social rates of return (e.g. a coefficient of 10 would be interpreted literally as a 1,000% marginal social return). Clearly, these would be implausible estimates of the social returns to public R&D investment. As a result we prefer to look at the sign, significance and comparison across types of investment as a way to gauge which appear to be most strongly positively correlated with private sector R&D growth, rather than interpreting the values of the estimates literally as social rates of return.

It is worth considering why the coefficients we estimate are so high, though, to aid the interpretation of the findings. A number of possibilities exist:

- To interpret the coefficients as rates of return, we have assumed no depreciation of publicly-funded R&D investments. Whilst this is quite a standard assumption in previous studies (see Section 2.4.2) it may not be applicable if we look at some of the more scientific and applied public investments which we explored in our analysis. However a typical assumption in the private R&D literature is that knowledge stocks depreciate at a rate of around 20 to 25% per year; given the size of our estimates even subtracting this figure to approximate a "net" return still leaves us with very high estimates of the social rate of return.

- Some of the cases where we find particularly large coefficients (experimental development research, for example) are those where the absolute level of investment is very low. At the margin the returns could be very high, but would decline as additional investment occurs and the "stock" of public knowledge is expanded. This intuition accords with the pattern of declining marginal returns we see as the sample period is expanded.

- We base our estimates entirely on aggregated, time series data. As discussed, given the short period of data available we prefer to minimise the number of control variables in order to pick up correlations between public R&D investments and private sector TFP growth as well as we can. However this leaves open possible omitted variable biases: if other factors are positively correlated with public R&D over time, and also positively influence private sector TFP, we would attribute their impact to the public investment. Our robustness checks (see Section 3.7) control for some other factors and find they make little difference to the results. However, given we are using time series data, we are unable to control for general time trends which might pick up exogenous technical progress, or "learning-by-doing" by which knowledge investments build on previous investments to generate returns.

The latter point seems particularly important. An alternative methodology which would allow controls for time trends in exogenous productivity growth to be captured would be to use industry- or firm-level panel data rather than aggregated time-series data. This would require disaggregate measures of TFP growth. It would also require the measure of public R&D investments to vary across the units of observation, and so require some way to measure how "closely" each industry in the sample draws on public investment.[54] As our case study evidence shows, there are clearly a number of industries (such as aerospace and life sciences) where interaction with publicly-funded knowledge investments is critical to driving innovation and so productivity, whereas there are likely to be other industries where this interaction is less important. We would therefore need to account for this closeness in measuring the impact of public R&D on industry-level TFP growth.

This analysis is beyond the scope of the current work, but is roughly the method used by Haskel et al. (2014) who find more reasonable estimates of around 20% for the social rate of return to public R&D using industry-level panel data. However they did not consider whether these returns varied by type of investment, which would be an interesting follow-on to their analysis.

3.7 Robustness of results

As described earlier we run a number of robustness checks. The main findings from these checks are shown in the tables in Appendix C. Our focus is on the robustness of the results by broad category of public R&D in **Table 5** and the pattern by sample period of research council investments in **Table 6**, though similar results have been estimated for the further decomposition of research council R&D.[55]

We find that the robustness checks in general make little qualitative difference to the main pattern of results from the analysis shown above.

3.7.1 Including intangible investments in the TFP measure

We obtained a measure of market sector TFP which had been corrected for investment in intangible assets (including scientific R&D and other intangibles), as was used by Haskel and Wallis (2010, 2013).[56] Using this measure does not alter our baseline conclusions (see **Table 17**): the social rate of return to research council expenditure is positive and significant, though the size and significance of the effect diminishes as we add additional years of data. The main difference

[54] This is similar to the way in which spillover effects looking at the impact of other firm or industry R&D require some assumption to be made about how close firms and industries are to each other to construct stocks of "external knowledge" which vary across units of observation.

[55] These results are available on request.

[56] We are grateful to Jonathan Haskel for supplying this data. Note that because this measure of TFP accounts for private sector R&D we no longer control for it in this robustness exercise.

appears to be that the return of higher education funding is negative and significant using the Haskel and Wallis TFP measure up to 2008.

3.7.2 Adding additional control variables

Our baseline results control only for particular measures of public R&D and private R&D. Given the limited degrees of freedom at our disposal, these results give us the best opportunity to pick up significant correlations between these investments and future private sector TFP growth. However we may of course be wary that these correlations reflect omitted variable biases if R&D is positively correlated with another variable which also increases market sector TFP.

Following Haskel and Wallis (2010, 2013) we therefore control for a number of additional factors which, at least at an aggregate level, may be expected to influence market sector TFP over time: changes in the penetration of internet access in the UK, the productivity gap between the US and the UK reflecting opportunities for catch-up productivity growth, and foreign government R&D expenditure reflecting possible international spillovers. These results are shown in **Table 18**.

Including these additional controls does not fundamentally affect the conclusions: the coefficients on the public R&D investments have the same sign, and the pattern of the social returns to research council investments as the sample period gets longer exhibits the same declining marginal return.

In terms of the control variables themselves, we find some tentative evidence that increases in foreign government public R&D have positive effects on UK market sector productivity, suggesting small international spillovers, and that increases in the internet penetration rate are later associated with some increase in private sector productivity. However these results are not always significant and, given the number of degrees of freedom in the model, may be difficult to pick up robustly.

3.7.3 The choice of smoothing measure

Our baseline specification used a smoothed TFP growth measure based on a simple moving average using the current and previous two years' observation.

The qualitative results do not appear to be particularly sensitive to using longer periods of smoothing (5 and 7 years), or (following Haskel and Wallis) using a lag and a lead of each year's TFP growth measure to construct the smoothed figure. The results of this sensitivity analysis (exploring the impact on the research council coefficients over different sample periods) are shown in **Table 19**.

Compared to our baseline estimates, we find very similar patterns of results using 5-year smoothing or taking lags and leads.[57] We find a similar pattern of diminishing coefficients using a 7-year smoothing, though the significance of the results in earlier years is lost. Using unsmoothed data, we find much less clear cut evidence of the diminishing trend in the size of the coefficient on research council investments, though as noted earlier it is not common practice to rely on unsmoothed TFP data for this kind of analysis.

3.7.4 The lag structure of R&D investments

Our baseline results use a two-year lagged measure of R&D relative to value added as an independent variable. We find little evidence that replacing this with a one-year or three-year lag materially affects the conclusions. Again, including longer lags becomes increasingly difficult given the sample size. These results are shown in **Table 20**.

3.8 Opportunities for further analysis

Our focus has been on drilling down into the research council R&D investments to assess whether there are differences in the social returns to particular forms of investment. However, a number of additional analyses could be conducted:

- **Sector analysis;** our results use market sector TFP and value added to analyse the social returns to R&D investments. It would be possible to conduct the analysis for particular sectors (e.g. manufacturing, agriculture).[58] If it is possible to match publicly-funded R&D with these sectors specifically, the effect of this R&D spending on these sectors could be measured.

- **Civil departments;** it would be possible to assess whether there were differences to the returns by different departmental R&D expenditures by categorising civil departments over time by broad function. This would need to be done in a relatively aggregated way given changes in the composition of civil departments over time. Again, we might hypothesise that some departmental R&D investments would be expected to have larger impacts on private sector TFP growth (e.g. business and industry spending may impact on industrial productivity; food and environment spending on agricultural productivity, and so on).

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[57] Note that when we include a lag and a lead we find a negative coefficient using the data to 2008; this could reflect the impact of very negative TFP growth in 2009 affecting the smoothed figure.

[58] Note that there are particular difficulties in looking at agriculture in isolation because of how to account for land inputs in TFP data: see Timmer et al (2007).

- **Total public investments of different Frascati activities;** our focus was on decomposing the research council investments, though it would be possible (at least for civil and defence) to construct Frascati decompositions for a wider measure of public investment. This may be interesting as civil and defence spending tends to be more heavily weighted towards applied and experimental development expenditure whereas research council spend, as we saw, tends to be more focused on basic research.

4 Case studies

4.1 Introduction and case study approach

Our review of the existing literature highlighted a number of gaps (see Section 2.5). Whilst we were able to explore more about the social returns to different forms of public R&D investments using econometric evidence (Section 3), a number of other issues appeared more amenable to additional evidence drawn from case studies. In particular, there was interest in exploring further some of the issues important to the pathways linking public R&D investments to innovations which increase economic activity, including:

- The lag times between public R&D investments and their commercialisation by industry in the form of product and process innovation;
- How long the benefits of innovation are expected to last, and what the profile of those returns looks like over time;
- How industry interacts with different forms of publicly-funded knowledge investments (including academic research, capital and current investments in science and research facilities, and financial incentives for private R&D) and how important these different kinds of public investments are in driving forward innovation;
- The extent to which public investments genuinely lead to additional innovation relative to what might otherwise have occurred, or whether they crowd out private investments;
- Evidence on the wider influences on how effective any engagement between private industry and publicly-funded R&D investments is in generating economic returns, or how this engagement could be made more effective.

To explore these issues in depth, we began by identifying key industries in which publicly-funded R&D was likely to be an important component of innovation, since these industries would probably yield the greatest insights into some of the issues highlighted. We drew on discussions with BIS, including industry teams, and an analysis of government strategy documents. In the end we selected the aerospace and life sciences sectors as two important sectors, clearly identified as of strategic interest, and where public knowledge investments were seen to be important. We describe the background to each sector in Sections 4.3.1 and 4.4.1.

Having identified the sectors of interest, we drew on discussions with the relevant BIS sector teams to identify potential companies with which we could conduct case study interviews.[59] In total we conducted interviews with four companies, two in each sector.

We drew up an approach to the case studies which consisted of two components:

- A general interview with one or more senior staff in the company with oversight of research and innovation issues, to address broad questions about the company's approach and strategy towards research and innovation, how the company engages with publicly-funded investments of different kinds to drive innovation forward, any barriers or difficulties in that engagement process, and how important publicly-funded investments are in generating innovation for the company.

- Follow-on interviews with other people from the company to explore a small number of examples of recent innovations in more depth, and the role that public investments played in that innovation. In particular, with these examples we wanted to explore some of the issues around lag times, expected duration and profile of returns and whether the innovation could have occurred without the public investment.

The interviews were semi-structured, and facilitated by a topic guide (see Appendix D) which set out the broad areas to explore. All interviews were (with permission) audio-recorded to allow a full write-up and synthesis of the evidence from each interview to be produced.

By their nature, case studies can only be informative about the particular company being studied and so wider extrapolation must be treated with some caution. In particular, the industries studied are known to share some quite similar characteristics in terms of lengthy lag times in research and innovation, of being global in nature (and so decisions about location are important) and of engaging in significant amounts of traditional, scientific R&D as part of the innovation process. However, these are clearly important strategic industries that engage heavily with the public sector, and so the findings are clearly of interest. Future research could usefully look at how other important sectors, less traditionally thought of as engaging in research and innovation, also draw on publicly-funded investments, or how they perceive their own investments in terms of driving innovation. These could include a large number of very important sectors such as energy, retail and other service-based sectors, which clearly make up a large share of the economy.

Before we go into the detail of the case study findings, we offer a short synthesis of the key findings, comparing across the sectors and within.

[59] We are grateful to those in the Office of Life Sciences and the Aerospace industry team who discussed these issues with us and helped us to contact firms in each sector.

4.2 Synthesis of findings

Both the aerospace and life sciences industries are characterised by long development cycles for new products, with large amounts of research and development (as well as other non-R&D) investments required to drive innovation. Successful innovation can be long-lived in both industries.

The scale of investment required increases in both industries as development gets closer to market, in aerospace because of the need to prove safety at larger scale in a real-world environment and in life sciences because of the costs of clinical trials. A key difference between the sectors is that investments in aerospace tend to focus on 'technologies' which have a number of potential applications, as a way of spreading the risk that any single innovation fails or is made rapidly obsolete. In developing new medicines, should a particular molecule fail to work as hoped it is much less likely to have any other direct application.

Both industries rely heavily on public investments to support the innovation process. In life sciences, this is more heavily focused on academia and early-stage collaboration to help companies absorb basic scientific knowledge and use that to help develop potential new treatments. There is an increasing use of 'catalyst' centres which are partly publicly-funded as a way to foster smaller start-up companies and help the development process. In aerospace, whilst collaboration with academia is also important, there is also a reliance on publicly-funded capital facilities which allow companies to test and develop new products at scale at later stages of development, in a way which would not be efficient for any single company to invest in the necessary facilities.

In both aerospace and life sciences, underpinning academic research does not necessarily have to be new to drive innovation. One aerospace company describes how they developed an alloy which contributed to the development of new engines entering service in 2008 drawing on chemistry research from the 1980s. One life sciences company acquired a biotech firm which was developing approaches to new treatments in the mid-2000s drawing on underpinning research from the late 1970s and 1980s.

In both industries, a high quality science base is seen to be a key driver of where firms locate their research investments. Companies place value on direct interaction with academic collaborators, and so proximity to science is important: this helps to build trust which is an important part of successful collaboration when the risks of failure are high.

Different companies are adopting different approaches to academic collaboration even within an industry, and it is not clear that there is one more effective 'model' of collaboration than another. Although increased collaboration between industry and academia suggests that companies believe the collaboration is generating positive returns, all companies found it hard to estimate a 'rate of return' to a particular investment project directly, or to decompose the returns they got from different forms of R&D investments. This reflects the fact that many different investments have to come together in order to innovate, suggesting that they are highly complementary.

It was not clear that the amount of money being invested directly by the public sector in R&D led directly to additional private investments by the companies interviewed. However, nor was it replacing investments the companies would otherwise have made themselves, and as noted investments in the basic science base in the UK did seem to influence decisions to invest private R&D here rather than elsewhere. Investments which help to reduce the length of development times (and so increase private returns) would also likely increase the amount of private investment – for example, in patient data in life sciences, or in capital facilities which speed up the development of large-scale technology in aerospace.

Public investments which reduce the risks around innovation in the sectors would also leverage additional private investment. In aerospace, for example, the need for continuity and certainty of public investment across the development cycle was seen to be critical; in life sciences, investment in the underpinning science gives companies confidence to invest in later stage development because this basic knowledge improvement reduces the risk of later failure.

4.3 Case study sector: Aerospace

4.3.1 Sector background

The UK is one of the world's leading aerospace manufacturing countries. In terms of civil aerospace (passenger and commercial aircraft), the UK has a market share of around 17%, the largest in Europe and second-largest in the world. The sector includes Original Equipment Manufacturers (OEMs) such as Airbus and Boeing, which assemble aircraft and sell to airlines and governments. The supply chain then includes a small number (10 to 20) of Tier One companies who provide key sub-sections of the aircraft, and a much larger number (over 1,000) of Tier Two, Three and Four companies who manufacture sub-sections and component parts.[60]

Growth in the sector is expected to be strong: it is expected that there will be a global requirement for over 27,000 new aircraft (worth approximately $3.7 trillion) by 2031. This is partly to renew aging fleets and partly because of new demand in the developing world. The UK Government has identified aerospace as a critical industry for the economy, publishing two key documents relating to

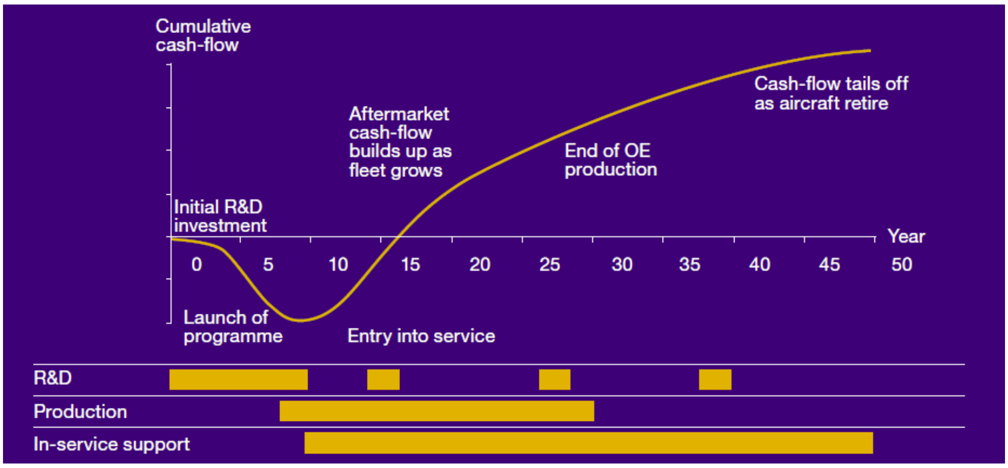
[60] KPMG (2013), *The Future of Civil Aerospace*, http://www.kpmg.com/UK/en/IssuesAndInsights/ArticlesPublications/Documents/PDF/Market%20Sector/AerospaceandDefence/the-future-of-civil-aerospace.pdf.

its strategy and the tools to implement it.[61] The strategy and its implementation have been developed under the Aerospace Growth Partnership, a collaboration between the Government and the UK aerospace industry formed in 2010. Four high-value areas where the UK should seek to maintain a competitive advantage have been identified as:

- Aerodynamics (aircraft design)
- Propulsion
- Aerostructures (fuselage and wing assembly)
- Advanced systems (avionics).

In terms of innovation, the industry is characterised by long development times and a lengthy financial returns profile, with considerable amounts of risk and uncertainty (see **Figure 13**). A new generation of single-aisle aircraft is expected by 2030 and development of these aircraft is starting now.

Figure 13. Illustrative example of product lifecycle for new passenger aircraft



Source: HM Government and AGP (2013), *Lifting Off – Implementing the Strategic Vision for UK Aerospace*

This development profile poses significant challenges in terms of funding investment. Timescales for a return on investment and the associated risks are too great for companies to bear on their own, and become harder to bear lower down the supply chain. A number of specific investments in the industry have therefore been made by the public sector in recent years, including:

61 "Reach for the Skies – A Strategic Vision for UK Aerospace", https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31807/12-954-reach-skies-strategic-vision-uk-aerospace.pdf
"Lifting Off – Implementing the Strategic Vision for UK Aerospace", https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/142625/Lifting_off_implementing_the_strategic_vision_for_UK_aerospace.pdf

- The UK Aerospace Technology Institute (ATI), receiving government funding of £150 million per year from 2014-15 to be matched by industry investment for at least the next 7 years. The ATI focuses on R&D in the four key areas identified by the Government strategy.
- The National Aerospace Technology Exploitation Programme (NATEP) is aimed at helping SMEs develop their own innovative technologies, receiving a total of £23 million of public funding over the next three years (with an additional £17 million of industry funding) through the TSB's Advanced Manufacturing Supply Chain Initiative.
- A £6m bursary to support 500 new masters level graduate places for aerospace, to be delivered between 2013 and 2017, has been established through joint Government and industry funding.
- The UK Aerodynamics Centre (£60 million public funding with £40 million commitment from industry) at Cranfield, aimed at developing and implementing aerodynamic technology research in the UK.

4.3.2 Case study 1: GKN Aerospace

Company background

GKN plc. is an engineering company which has been established for more than 250 years. The company is formed of four major divisions:

- Driveline (automotive)
- Aerospace
- Land systems
- Powder metallurgy

GKN Aerospace is a leading Tier One supplier to the industry, with customers including Airbus and Boeing. The Aerospace part of GKN has grown rapidly to become the second-largest division of the company in recent years. Turnover in the division has risen from around £500 million ten years ago to £2.24 billion. GKN Aerospace now employs around 12,000 people at 35 sites across the world. Around 73% of turnover is derived from civil aerospace, and 27% from military. The majority of sales come from aero-engines (50% of sales in 2013).

Growing the aerospace part of the business was a strategic decision by the company after identifying civil aerospace as a growth area both in established and emerging markets. The growth of the aerospace division at GKN has been achieved via a series of strategic acquisitions as well as securing positions on the key future aircraft programmes. A key part of this strategy has also been to migrate the portfolio from a military bias towards a commercial bias to support the significant growth in commercial aerospace.

Case study summary of key findings

- Investment in large aircraft components is characterised by long development times and a lengthy financial returns profile, with considerable amounts of risk and uncertainty for those making investment decisions. Timescales for a return and the associated risks are too great for companies to bear on their own, and become harder to bear lower down the supply chain.

- Due to uncertainties around the precise technical requirements of new aircraft, research investments are often focused on strands of technology – which may have a range of applications – rather than on specific products.

- It is very difficult for GKN Aerospace to decompose the precise contribution of an individual investment – or of a specific type of investment (e.g. capital spending) – to an individual return in a meaningful way. Initial programmes of research to develop new technologies are then built on by subsequent investments, including public investments, all of which contribute to the final returns.

- Given the global nature of the aerospace industry, public support to R&D is a key driver of the location of private investment. Firms like GKN Aerospace locate their R&D activities where the potential for conducting high-quality research is highest. This is determined by public investment in R&D, through the expertise, facilities, and opportunities available at all stages of technology development – from the initial academic research to the final testing.

- The total amount of investment in R&D made by GKN Aerospace is primarily affected by strategic considerations on the development of the sector, rather than by the availability of public funding.

- The continuity of public support across the development process was identified by GKN Aerospace as a critical need. Although later stages of the development process involve lower risk, they also require increasing financial resources and present their own technical challenges.

- GKN Aerospace engages in collaborations with academia to develop newly emerging technologies towards commercial applications in the long term. Physical proximity to academic institutions is a key driver of the quality of collaborations. This is in part through greater mutual understanding of the challenges faced in a particular area of technology. Moreover, an increased coordination and integration of expertise across academic institutions may remove existing barriers to engagement beyond local networks.

- The technology and innovation centres under the High Value Manufacturing Catapult, with which GKN Aerospace interacts at later stages of technology development, are perceived as a successful example of coordination of public investment in an area of technology.

Research and innovation at GKN Aerospace

The innovation process

A standard industry approach considers innovation around the idea of Technology Readiness Levels (TRLs) as defined by NASA, used to assess how close technologies are to market. The process of developing a new technology to market readiness can be thought of as composed of three stages (see **Figure 14**). As each stage moves forward, there is a different level of testing, a different role for public investment, and an increased size of investment required though a lower overall risk that the technology will not ultimately be able to reach market. However, critically, public investments are considered to be important across the whole process rather than at any individual part of it – we return to this below.

Figure 14. TRL development process

	TRL 1–3 Development	TRL 4–6 Industrialisation	TRL 7–9 Proving
Level of testing required	Laboratory scale	Scaled testing	Testing in real environment
Role of public investments	Universities and research councils: blue-sky ideas	Catapult Centres (e.g. NCC): capital facilities for scaling applied research Technology Strategy Board: research, linkages	Local Enterprise Partnerships, Regional Growth Funds, government loans: help industrialise high risk projects
Size of investments required	Smaller	Larger	Largest
Probability of failure	High	Lower	Lowest

Source: Frontier Economics, based on interview with GKN Aerospace

Because of the scale of the investment involved in designing and producing an aircraft, and the long service life of new aircraft (which can be up to 40 or even 50 years), innovation in aerospace aims at achieving significant step changes. This includes the recent move to lightweight composite materials in aerostructures, which has been a significant innovation in aircraft design, helping to reduce weight and thereby fuel consumption (see box).

Composites in aircraft

Over the last 20 years, GKN Aerospace has significantly developed their capability in composite materials for aircraft structures. GKN Aerospace now uses composite materials in a number of their products or innovation programmes, including wing spars, landing flaps, trailing edges and winglets.

GKN Aerospace's investment in composites was driven by a clearly identified market need to increase the fuel efficiency of aircraft, which has already led to step changes in aircraft performance (newer aircraft are around 50% more fuel efficient than 15 years ago, and composites make up approximately 50% of the structural weight of aircraft such as the Boeing 787 and the Airbus A350 XWB, a proportion which is expected to increase in future generation aircraft). The drive for lighter, more fuel-efficient aircraft stems mostly from increases in the cost of aviation fuel, though emissions- and noise-related legislation are expected to be more important influences in the future.

A number of individual product and process innovations are, of course, critical to delivering this step-change. New technological development (such as developing composite materials, where GKN Aerospace in particular has been a key investor and innovator) can take 10 to 15 years (or even longer) from proof of concept to application.

Drivers of innovation

For GKN Aerospace, the main drivers of innovation are strategic decisions made by their ultimate customers – the OEMs – about what the next generation of aircraft will need to look like. This in turn can be driven by a range of factors, both global and local, including projections of passenger demand and passenger preferences, macroeconomic conditions, regulation and legislation, and so on. Most of the market research which influences these strategic decisions is being undertaken by the OEMs themselves rather by than Tier One suppliers like GKN Aerospace.

From the point at which decisions are made by OEMs about their plans for the next generation of aircraft, it can take 7 or 8 years to develop the aircraft itself. This comprises around 5 years' development time and an additional 2 years or so for flight testing and certification. Safety and the regulatory environment are crucial to the industry: new aircraft are extensively tested in extreme conditions to prove their airworthiness and passenger safety.

Given the identified needs of the OEMs, GKN Aerospace's innovation strategy is based on identifying the technologies which enable those needs to be met and whether GKN Aerospace are well-placed to contribute to innovation in those technologies. This includes decisions about how big the potential market opportunities are likely to be and the sorts of investments which might be needed to develop the technology. The strategy is also influenced by issues such as ensuring a diversified customer base, a balanced portfolio of products, resilience to potential market shocks and trying to smooth revenue flows over time across the portfolio.

Once decisions have been made about which enabling technologies to develop, GKN Aerospace often works collaboratively with key customers to conduct the research. Given the size of investments required, there could be significant duplication of effort and resource costs if a number of suppliers are developing the same technologies at the same time. Because of uncertainties around precisely when new aircraft designs will be needed and put into service, a key driver for GKN Aerospace is that their innovations and research investments (often focused on strands of technology rather than specific products) have a range of applications which can be put into place into existing aircraft.

There is a significant amount of process innovation at GKN Aerospace, in particular aimed at reducing manufacturing times. Automation is a key part of this, and a specific example in the case of manufacturing winglets is described in the box below.

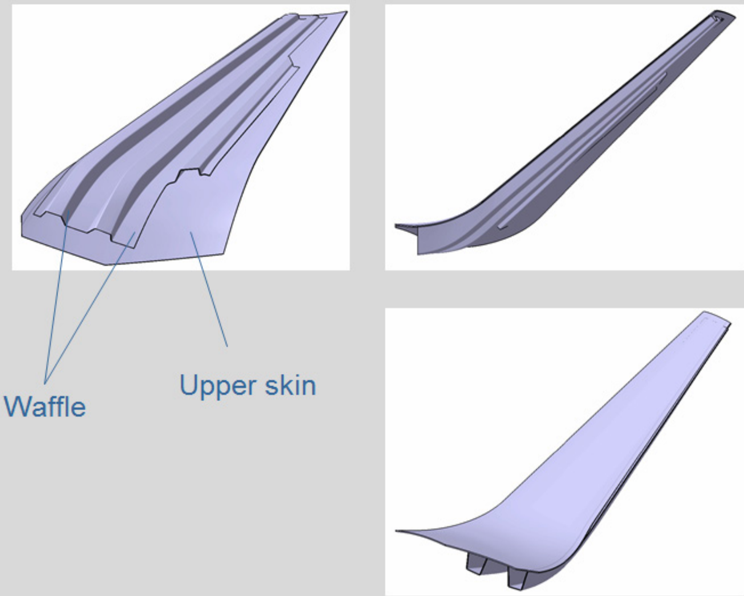
Developing automated process: winglets

Winglets are wing tip extensions that have become an established feature of wing design, because they provide valuable benefits in increased aircraft rate of climb, reduced fuel burn, and a reduced noise footprint by reducing lift induced drag.

GKN Aerospace first started producing winglets in 2003, when Airbus commissioned the manufacturing of winglets for flight testing, to assess their alleged benefits in terms of fuel saving. This initial commission gave GKN Aerospace credibility to win follow-on work, including the manufacture of winglets for Boeing's 737 aircraft and the design and build of a larger winglet for Boeing's 767.

In 2007, GKN Aerospace began an R&T programme aimed at significantly reducing production costs through increased use of automation in the process by which parts, including winglets, are manufactured. In the winglet case, for example, the structure is comprised of an internal 'spar-and-rib' structure (called a 'waffle') with outer skins which are fastened together currently using a manual, labour-intensive process. The challenge was to find a way to produce the inner structure and one half of the outer skin as a single piece which can be co-cured at the same time in an autoclave, with the second half of the skin then fastened robotically using a technique called auto-drill and fasten (see **Figure 15**).

Figure 15. Waffle design concept for a single aisle aircraft



Source: GKN Aerospace

This automated process has the potential to reduce assembly times by around 75% and cut costs by around 20% overall.

The R&T programme is not specific to the manufacture of winglets, and the techniques could also be applied to other products – outlining the importance of investment not just in a product, but in a technology strand with a number of potential applications.

The research started as a small programme entirely funded by GKN Aerospace, but is now (from around TRL 3 onwards) being developed with 50% matched support from public investments. This kind of support is seen as critical in order to develop innovative technologies and method given the costs and time-frames involved in the process. Without the support, it was felt that the development may have stopped at around TRL 3, or may have been continued abroad instead.

The programme is expected to reach a TRL 5 (close to being ready for final testing) by around 2016. Getting the process innovation to this phase would therefore have taken around 9 years.

Public support for developing the process has come from a number of sources:

- First, the project was submitted in 2010 to the "Composites Grand Challenge", a competition run by the Technology Strategy Board for companies to collaborate to progress innovations in composite manufacturing technologies, offering 50% funding to the companies. The competition was won by a consortium led by GKN Aerospace, gaining £5 million in co-funding. This 1-year funding helped to meet tooling costs, and develop the innovation to around TRL 2 to 3.

- The project was then further developed through the collaborative STeM (Structures Technology Maturity) programme, including GKN Aerospace in partnership with Bombardier, Spirit, and General Electric. STeM also received support from TSB to fund 50% of the development costs. Further development also took place at the Advanced Manufacturing Research Centre (AMRC) in Sheffield, one of the centres in the network of the High Value Manufacturing Catapult. GKN Aerospace subcontracted some of the work to AMRC staff with expertise in the necessary processes; this saved employing, training and maintaining a dedicated in-house team to drive the innovation forward, and allowed knowledge to flow between GKN Aerospace and AMRC staff. Another value of Catapults for GKN Aerospace is that they are 'neutral' in terms of giving an honest assessment of how long the work will take and the results provided, and in being able to source hardware and software from any supplier. These were perceived as benefits over an alternative approach of running a competition to subcontract the work to other companies.
- Further development is now planned through a funding bid submitted to the Aerospace Technology Institute to take the process to TRL 5 by 2016, which also includes a substantial amount of work with the Catapult. One of the key values of ATI funding identified by GKN Aerospace is the long-term nature of the investment which allows companies like GKN Aerospace to invest more strategically in technology development. Previously, companies had to bid into a series of short-term programmes to continue development, bending the development to the needs of the specific funding opportunity and leaving more uncertainty about the availability of funding for further development at the end of each specific contract.

For technologies like winglets, there is always the risk of disruptive innovation by OEMs which could make current designs essentially obsolete (for example, new shapes of winglet which are found to be more efficient at reducing drag). As a result the expected profile of any returns to developing this technology is very difficult to predict, and again emphasises the value in this sector of innovation focused on technological processes which have wider application rather than those which can only be used to produce a single end product.

More generally, GKN Aerospace try to partner with a range of other manufacturing, automation and design companies at an early stage to develop machines and technologies for automation. These companies include existing GKN Aerospace suppliers and some companies with whom they have no previous relationship. To drive this process, GKN Aerospace tend to develop a specification for their requirements and then look for other companies to suggest ways (singly or in collaboration) to help meet those requirements. While GKN Aerospace recognises the opportunities and incentives for such inter-business partnership, they felt that in general public policy could do more to encourage investment in this kind of collaborative process innovation, based on the potential for knowledge spillovers to occur across the supply chain.

The research process

GKN Aerospace's research is run centrally, rather than individually at their various sites across the globe. This helps to avoid duplication of effort across sites and maximises the productivity of the research itself, but there is difficulty disseminating the internal research findings and deploying the resulting technologies *within* the company across the sites.

Once the required research investments have been identified, GKN Aerospace's approach is to find the most effective location for and method of doing the research. Given the global nature of the aerospace industry, public investments supporting R&D are a key influence on where firms like GKN Aerospace locate their research activities. The optimal global location for all significant research investments is considered, as part of the overall centralisation of research decisions. The choice of location for research is not simply dictated by the value of public support that may be offered in different jurisdictions. Other factors in the decision include current expertise at the sites and how the support links across the whole technology development lifecycle, moving from academic support and collaboration to develop early stage ideas, through to industrialisation and then final proving and commercialisation. This *continuity* of support across the development process was identified by GKN Aerospace as a critical need.

Total amounts to invest in research and technology and the research needs are set as a top-down decision by the GKN Aerospace board, and are not in themselves thought to be affected by public investments. Government funding and support can help to influence the decisions about where and how investments are made, however.

Measuring the returns to investment in innovation

Demonstrating a return on research and technology investments in terms of expected increases in sales is critical, though it is recognised to be difficult to measure the returns with complete accuracy. GKN Aerospace has a technology readiness review process as development moves along the chain outlined in **Figure 14**. At each broad transition point, a "gate review" takes place to assess whether the investments are achieving their objectives and the state of the route to market at that point. Projects which are not thought likely to succeed and generate the required returns are dropped as part of this review process.

Although GKN Aerospace can trace back particular investments which contributed directly to particular new contracts and sales, it was said to be very hard to decompose the precise contribution of an individual investment to an individual return in a meaningful way. Initial programmes of research to develop new technologies are then built on by subsequent investments, including public investments, all of which contribute to the final returns. For example, the ALCAST (Advanced Low Cost Aircraft Structures) programme was set up in 2005 with approximately €50 million of EU funding and €50 million of industry funding. It contributed directly to the composite wing industry being established for commercial and military aircraft in Europe, since it saw the first complete composite wing developed for Airbus.[62] Again, though, trying to isolate the contribution of a single programme to the overall returns for a company in terms of sales is extremely hard, since it requires the initial fundamental research in composites, and then public and private capital and resource investments to commercialise the idea over a lengthy development period.

Interactions with publicly-funded investments

The rationale for public investment in innovation for aerospace

Although GKN Aerospace fund most of their research and innovation investments directly from retained profits, there was felt to be a clear need for additional public investment to support the process. This is because of the large upfront costs of developing new technologies, the long lag times in this development process, market risks and lengthy payback periods, which make investment by private investors relatively unattractive. Market risks over such a long period include changes in consumer tastes and preferences for different forms of transport, changes in flight patterns, global shocks, disruptive technological change, etc.

Interactions with academia

All of GKN Aerospace's interaction with academic research is done with commercial application in mind: they do not conduct purely basic research. However, while GKN Aerospace have specific requirements of the research they fund or draw on, this can involve assessing the potential value of basic research or newly-emerging technologies at a very early stage of development, without necessarily having a clear final application at that point.

At the first stage in developing an innovative idea (TRL 1–3), GKN Aerospace interacts with academia directly and participates in research projects which are co-funded between GKN Aerospace and research councils (primarily the EPSRC). Knowledge exchange which helps develop these relationships flows both ways: academics 'push' new ideas to GKN Aerospace, or GKN Aerospace will 'pull' in academics by setting requirements based on expected future commercial needs to the universities themselves to see if they can develop ideas for technological solutions.

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[62] http://ec.europa.eu/research/transport/projects/items/alcast_en.htm

Because of the strong interest in composite materials, GKN Aerospace has actively sought to interact with the academic research taking place in the field. The company has developed a close relationship with the University of Bath, where it is sponsoring a research chair in composite structures analysis, co-funded by the Royal Academy of Engineering. The chair is currently held by Professor Richard Butler, who had previously worked at GKN Aerospace under a Royal Academy of Engineering secondment scheme. This enabled him to see the needs of the company and on that basis to propose a plan of work which could be done collaboratively between Bath and GKN Aerospace which had both academic and commercial benefit. GKN Aerospace also co-funds PhD students in the Bath research group, setting projects into the group based on early stage ideas that may develop new, useful composite technologies in 10 to 15 years' time. Some of the work with Professor Butler is helping develop mathematical modelling tools which could help reduce costs for the business significantly in the future (see box).

Developing models to predict defects in composite structures

A crucial issue in developing composite parts is that as they become larger, there is a significant risk of defects occurring. Given the enormously exacting safety standards in the industry, there is a clear need to prevent this and understand how and why these defects occur. At present, GKN Aerospace's approach is largely based on active experimentation: building components at larger scale, looking for defects, hypothesising about their cause and then rebuilding to see if the problem is solved. This involves considerable time and expense in terms of wasted composite materials. If it were possible to model defects more accurately before anything was built, this could bring considerable benefits in terms of materials and reduced development time. Indeed, the benefits of mathematical and computer simulation could be felt in a number of different applications. Realising this potential, in part based on observing what other companies were doing when GKN Aerospace took over Volvo Aerospace in 2012, GKN Aerospace have decided to invest funding into researching and developing these methods.

This involves considerable collaboration with academia. GKN Aerospace is currently co-funding a £481,000 EPSRC project with Professor Butler at Bath as the Principal Investigator (GKN Aerospace's financial contribution is around £82,000). The project is in collaboration with the geology, mathematics and engineering departments at Bath University to take mathematical modelling techniques used to predict the impact of earthquakes on sedimentary rock formations and applying them to understand how composite structures deform during manufacturing processes. The aim of the research will be to prove and certify the methodology, which would then help it to be used in the certification of aircraft structures aimed at developing mathematical modelling of aerospace composites to reduce significantly design-to-manufacture time. The project is expected to lead to some relatively well advanced process innovations (around TRL 4 to 5) in a period of 4 to 5 years.

This research is not something that GKN Aerospace could have developed purely based on internal knowledge, and where the access to the academic connections and network through the Bath collaboration was seen as critically important.

More broadly, GKN Aerospace operates a network of university linkages around the world based on those who can contribute to their commercial strategy in some way. They also work with the University of Bristol, who are the host institution for the National Composites Centre. GKN Aerospace have also partnered with university spin-off companies to develop internally process innovations around how composite components should best be moulded. The spin-off company (identified through an internal network) had developed software which allowed for better modelling of the results of a particular moulding technique, which GKN Aerospace could use and develop with their data from a particular example, allowing them to predict better the results of future applications of the moulding technique.

As well as institutional expertise which relates to commercial needs, proximity between GKN Aerospace and academic institutions is also a driver of collaboration. Proximity to research expertise helps to drive interaction between GKN Aerospace and academics. Having a presence within the institution through secondments or other staff exchanges (including PhD placements at GKN) and regular visits between GKN and the institutions helps to improve the quality of collaboration in a way which could not be achieved by virtual connections. GKN does conduct arms'-length research with more distant academic institutions, but their core activity requires reasonable proximity between academics and the company (as well as to facilities such as those at the National Composites Centre). Research that is conducted with more local institutions tends to have a higher chance of generating successful outcomes in terms of making it into commercial application, in part because the academic researchers have a clearer understanding of the commercial needs of the activity.

Other than established networks, GKN Aerospace try to absorb academic knowledge through paper-based research, attending dissemination events, conferences and so on. However there is relatively little investment in exhaustive academic literature searches, with a preference for network and knowledge-driven collaboration with academia. Places such as the NCC and TSB's Knowledge Transfer Networks (KTNs) are now seen to be starting to take on that role of reviewing and disseminating academic knowledge to industry, and at least for GKN Aerospace this is not simply replacing research investments they would themselves have otherwise made.

In some cases, research which is done in partnership with academics could be done entirely in-house. However, the academic researchers typically have already built up relevant knowledge, software and experience which it would take GKN Aerospace time to replicate. Given the need to try to deliver results quickly when developing new technologies, and the uncertainties around the precise knowledge which will ultimately be required in order to drive the development forward, it is usually preferable where possible to leverage that existing expertise rather than trying to recreate it internally.

Perceived barriers to engagement with academia

A potential barrier to academic engagement for GKN Aerospace is awareness: being able to identify the institutions and individuals with the relevant aerospace (or wider) expertise required to help the company develop its commercial needs. There is a sense of a dilution and spread of capability into small, overlapping departments across the country and a lack of clear world-class 'centres of excellence' for the sort of research which might be useful to the company. The current structure of academic departments makes engagement difficult, requiring significant resource and time investments to identify the right people and institutions (though reputation and results from e.g. the RAE are used to help try and do so). This is another reason why trusted, local relationships with key academics, and the networks which originate from those relationships, are often used to identify potential partnership opportunities for research. However, GKN Aerospace suggest that as a result they miss out on picking up on academic work which may have been useful to them, even when they have been able to articulate a specific need and where they suspect academics (or sometimes other companies) have been working on developing the technologies to solve the issue of interest.

GKN Aerospace would like to be able to develop closer, more strategic relationships with a wider network of academic institutions, and suggested that a move towards 'impact' as a factor in institutional assessment may help to make this happen, though it was not currently thought to be a high priority for most departments.

Interactions with publicly-funded science facilities

Innovative, potentially commercial ideas which are uncovered through links with academia or are otherwise picked up at a relatively early stage can be taken forward internally by GKN Aerospace or developed collaboratively at a publicly-funded centre. In the case of composite materials, for example, GKN Aerospace has a private development facility at Cowes on the Isle of Wight where they have a UK Composites Centre of Excellence,[63] and they are a Tier 1 member of the National Composites Centre (see box) based near to a couple of key GKN

[63] Note that this facility was also built with support from public funding: around two-thirds of the costs of the research centre and composite spar development centre were met through funding from the (then) DTI and the former Regional Development Agency.

Aerospace facilities just outside Bristol. Development can be done in either or both places.

The National Composites Centre

The NCC is an open-access facility which aims to be a hub for research in composites in the UK[64] It provides, among other things, access to capital equipment which can be used by companies, either directly or through the NCCs own core staff. It also provides a place for people from industry, government and academia with an interest in composites to meet.

The NCC was set up following the publication of the Government's composites strategy in 2009.[65] The University of Bristol is the host institution, though the NCC itself is located in the Bristol and Bath Science Park. The NCC and was set up with a £25 million investment from BIS, the European Regional Development Fund and the South West Regional Development Agency, and opened in 2011. It is one of seven technology and innovation centres overseen by the Technology Strategy Board as part of the High Value Manufacturing Catapult. GKN Aerospace is one of the founding partners of the NCC. Although corporate partners did not contribute directly to funding the NCC when it was set up, they contribute annual membership fees which pay for the operating costs. The 2012 Autumn Statement announced an additional £28 million investment in Phase II of the NCC which will increase its size, provide a dedicated high-speed composite manufacturing facility and a training facility. It is hoped that this will increase the presence at the NCC of other sectors besides aerospace, since the potential applications of composites are much wider (e.g. in automotive). This would increase the scope for cross-sector collaboration and spillover benefits. It is also hoped that the NCC will be used by a wider range of academic institutions and SMEs in the future to improve interaction between business and academia.

GKN Aerospace are one of the few aerospace companies to have a permanent presence at the NCC: they have around 30 staff permanently based there (Airbus has 60 staff there, and GKN Aerospace are seeking to expand their numbers there). The main value for GKN Aerospace of having a permanent presence at the NCC (other than being alongside one of their biggest customers) is an ability to help develop the strategy and content of the Centre, and a much stronger ability to collaborate with others.

The technology in the form of the state-of-the-art automated equipment which is available at the NCC tends to improve at relatively rapid rates. Companies are

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64 http://www.nccuk.com/

65 http://www.bis.gov.uk/~/media/biscore/corporate/docs/c/composites-strategy.pdf

reluctant to invest in equipment that they may not regularly use or which might be obsolete after a very short period.

Decisions over where to develop ideas emerging from academia are driven by a number of factors, including:

- public funding incentives;
- whether GKN Aerospace has private access to the facilities which would be needed;
- commercial sensitivities around keeping the development private;
- the need for help from other specialists based at the NCC;
- the value of collaborative development with customers or suppliers.

To some extent, development work which takes place at the NCC *could* in some cases have been done privately by GKN Aerospace; however, this is not always the case and the private and publicly-funded facilities are not fully substitutable for one another in terms of what can be done there. For example, the much larger space available at the NCC allows larger composite structures to be developed and tested than would be possible at GKN Aerospace's Isle of Wight facility. GKN Aerospace pays membership fees and fees to access the capital equipment at the NCC as well, and can sub-contract some of their work to NCC staff as needed. The value of the NCC is not therefore limited to the capital facilities, but also the current resource investments made to run and staff the Centre.

Some of the development work which GKN Aerospace can do at the NCC allows them to undertake preliminary testing of ideas before investing in their own capital equipment, which can help reduce some of the uncertainties around large-scale capital investment.

Another role of the NCC valued by companies like GKN Aerospace is to take on a role of identifying the key academic networks (individuals and institutions) in composites research. Given the fragmentation of academic composites research identified by GKN Aerospace as a potential barrier to academic engagement, having a central, university-hosted organisation able to take on a role of helping co-ordinate knowledge transfer from academia to industry is seen as very valuable.

Use of loans and grants

At the third stage of technological development (TRL 7–9), the new technology is tested in real-world conditions, which means that the cost of testing grows further, although the uncertainty around the success of the innovation is now reduced compared to earlier stages of its development. Public funding here is seen to be important in helping final industrialisation of the large-scale investments given the long payback periods.

Public investment can take the form of repayable loans for R&D that can be used to support the firm's own private investments (see box). GKN Aerospace also draws on EU grants (usually co-funded with UK public money and contributions from a number of companies engaged in collaborative projects), such as those available to EU development areas, and on TSB funded collaborative projects.

Public loans to support large-scale R&D projects

Having been chosen by Airbus in 2007 as the preferred bidder to purchase manufacturing facilities in Bristol and to carry out R&D to design and manufacture wing structures (spars and fixed trailing edges) for the A350 XWB, GKN Aerospace received a £60 million loan from the government to help pay for the R&D work. This was around one-third of the estimated cost of the entire R&D project (expected to last until 2015). To comply with EU State Aid rules, it had to be demonstrated that there was the potential for significant knowledge spillovers to GKN Aerospace's suppliers and other companies, and that private external funding could not have been found given the risks and lengthy payback periods involved. The internal rate of return of the R&D project, estimated at around 9 to 10.5% without the loan being received, was not considered enough given the risks involved to pass standard 'hurdle rates' for investments in the industry, estimated at 12.5-14.5%.[66]

4.3.3 Case study 2: Rolls-Royce

Company background

Rolls-Royce Holdings plc. is a multinational company providing integrated power solutions in five business segments:

- Civil aerospace
- Defence aerospace
- Marine
- Energy
- Power systems

In civil aerospace, Rolls-Royce produces and provides servicing for commercial aircraft engines. As of 2013, this is the largest segment by revenue generated, at around £6.7 billion, or 42% of total group revenues.[67] Within this sector, over

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[66] http://ec.europa.eu/competition/state_aid/cases/231824/231824_994773_57_2.pdf

[67] Revenue and market share data in this section are based on the Rolls-Royce Holdings plc. 2013 Annual Report (http://www.rolls-royce.com/Images/RR_Full%20Annual%20Report__tcm92-55530.pdf)

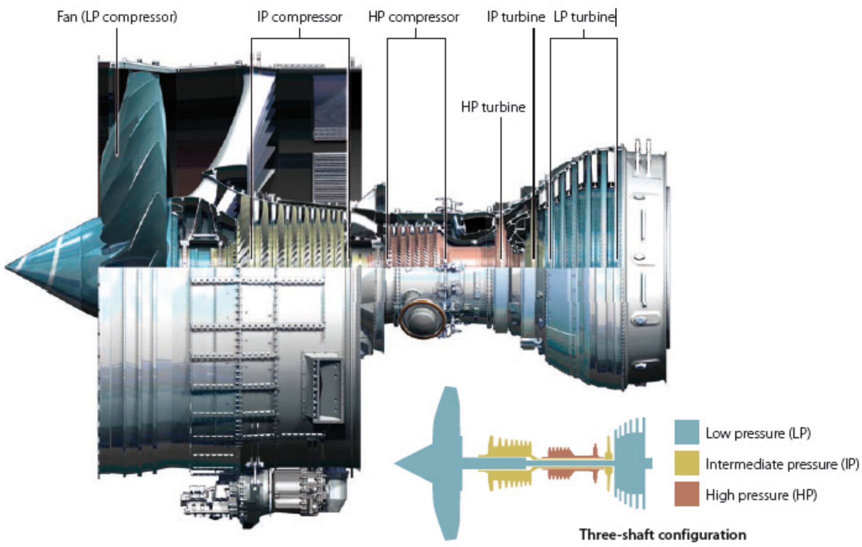
50% of revenue is generated through large engines for wide-body aircraft, a market where Rolls-Royce had a 54% share of aircraft on order in 2013.

Gas Turbine technology in a jet engine

Rolls-Royce's civil large engines are based on the gas turbine technology (see **Figure 16**). A gas turbine is a machine that burns fuel to provide energy to create a moving flow of air. In the case of modern jet engines, the power generated by the turbine is used to drive a large fan on the front of the engine that draws air backwards, producing thrust.

A gas turbine engine is composed of four main parts: fan system, compressor, combustor and turbine. The fan draws air at the front of the engine. A significant volume of this air exits the engine at its back, contributing the largest proportion of the engine's thrust. The remaining air drawn at the front gets delivered at a high pressure through the compressor to the combustor, where fuel is burnt. The turbine converts the energy stored within the hot gas produced by the combustion into kinetic energy.

Figure 16. Structure of a three-shaft large civil turbofan



Source: Rolls-Royce, "Gas turbine technology - introduction to a jet engine"

Rolls-Royce serves the wide-body market mainly through the Trent family of engines. Individual engine models are optimised for a specific aircraft. For example, the Trent 900 powers the Airbus A380; the Trent 1000 is designed for the Boeing 787; the Trent XWB for the Airbus A350. However, an aeroplane can often be equipped with different engines according to the preferences of the final customer. For instance, the Boeing 787 Dreamliner can be fitted either with the

Rolls-Royce Trent 1000 or with the General Electric GEnx, and the Trent 1000 has won 50% market share in contested Boeing 787 competitions to this date.[68]

Case study summary of key findings

- Investment in science and innovation is considered crucial to maintaining competitive advantage on the market. This mainly takes the form of "traditional" investment in R&D. However, spending on developing the adequate tools (for example, IT capability) and staff (for example, through training) is integral to the firm's strategy to achieving innovation.
- Innovations employed in new aerospace engines generate returns over several decades. It can take up to 20 years from the initial investment in the innovation to realise it in a product.
- Structured public sector support to investment in innovation in the sector mitigates the risks borne by private firms and can leverage additional private investment. To be effective support has to be consistent over time and over the stages of the development process, and may involve agreed long term goals of the innovation efforts between public and private sectors.
- Engagement with academia is fundamental for Rolls-Royce to be involved at the frontier of research that will shape the future generation of products. Rolls-Royce has created a network of academic institutions – the majority of which are in the UK – with which the firm has established long-term collaborative relationships. There is scope for the public sector to foster industry-university relationships, by enhancing the coordination of public investment within academia, and between academic and other public institutions.
- Rolls-Royce's R&D strategy is largely defined through very long term business plans identifying a range of technological innovations which may lead to the development of a new product. Rolls-Royce does not consider it plausible to measure the returns to a specific investment, or to a specific type of spending (e.g. current versus capital investment).

Research and innovation at Rolls-Royce

The innovation process

The aerospace sector is characterised by large scale of investment and long timeframes for product development. Investment in research and innovation on a continuous basis is therefore essential for established firms to preserve their position in the market. This primarily takes the form of "traditional" investment in technology: in 2013, Rolls-Royce spent approximately £1.2 billion on Research & Development – approximately 5% of the Group's annual revenue in that

[68] http://www.rolls-royce.com/civil/products/largeaircraft/trent_1000/

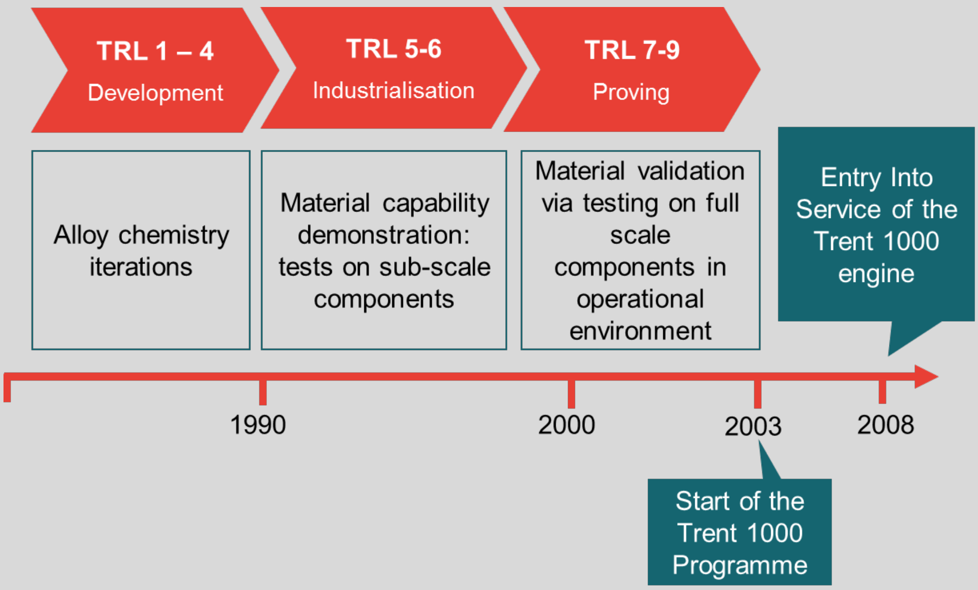
year.[69] Besides R&D, achieving innovation also requires investing in adequate tools and staff. In 2013, Rolls-Royce invested substantially in IT (over £100 million), and training (employing over 1,000 apprentices and around 300 graduate students).

Rolls-Royce's investment is spread over the entire TRL scale, ranging from the initial observation of basic principles in scientific research (TRL 1) to the final testing of an innovation in an operational environment (TRL 7-8), leading to entry into service (TRL 9). Given the complexity of the final product, a new engine as delivered to customers involves a large number of distinct innovations. The time required for a specific innovation to reach the market can be even longer than the timescale involved in reaching TRL 9.

The development of a new material for turbine discs

Figure 17 below shows the example of the RR1000 material, a nickel-based super-alloy developed at Rolls-Royce to meet the demand for turbine discs able to withstand higher temperatures and rotational speeds. Initial chemical research into this material begun in the 1980s – Rolls-Royce was involved in the early stages of development of the technology through collaborations with academia. TRL 9 was reached around twenty years later – but it took 5 more years since then for the Trent 1000 programme to deliver a final product.

Figure 17. Development timeline of the RR1000 nickel alloy



The investment in the development of the RR1000 alloy is an example of continuous involvement in shaping technologies that are eventually going to be

[69] Rolls-Royce Holdings plc. 2013 Annual Report (http://www.rolls-royce.com/Images/RR_Full%20Annual%20Report__tcm92-55530.pdf)

used in a future generation of engines. Along with this, Rolls-Royce also looks at shorter time horizons, to incorporate new technology in products that are closer to market, or to solve challenges posed by products in service.

Drivers of innovation

The characteristics of engines are a crucial determinant of the environmental performance of aircraft. The demand for improved environmental performance is therefore the main driver of innovation in aerospace engines, as a result of:

- Customer demand for reduced fuel consumption, following from rising fuel prices. Small increases in engine efficiency can generate very large financial savings for airlines: it has been estimated that a 1% efficiency gain across the entire fleet to one major European airline alone would generate financial savings worth around £40 million per year.
- Targets in terms of pollution emissions set by government and industry. The most important targets are those set by public and private stakeholders through ACARE – the Advisory Council for Aviation Research and Innovation in Europe. The ACARE goals are set relative to the capabilities of typical new aircraft in 2000, and include, by 2050:[70]
    - A 65% reduction in perceived noise emissions;
    - A 90% reduction in NOx emissions;
    - A 75% reduction in CO_2 emissions.

  The potential for these targets to stimulate innovation above and beyond what would be driven by customer demand alone arises as a result of their long-term focus and the related commitment by the public sector to consistent co-funding of R&D. This commitment reduces the risk facing individual firms and therefore increases their willingness to invest.
- Along with the ACARE targets, the Aerospace industry is also increasingly faced with legal requirements at the national level – in particular, requirements in terms of noise and NOx emissions aimed at protecting the local environment around airports.

The research process

Rolls-Royce's delivery model for the acquisition of new technology is centred around three pillars which broadly reflect the three stages of technology readiness as described in **Figure 17** above.

Unlike a number of other firms in the aerospace sector, Rolls-Royce does not have large in-house research facilities. Although research is managed centrally,

70 European Commission (2011), *Flightpath 2050 – Europe's Vision for Aviation*, (http://ec.europa.eu/transport/modes/air/doc/flightpath2050.pdf)

almost all the research taking place at TRL 1–4 is carried out through the company's network of University Technology Centres (UTCs, see below). UTCs are also occasionally used to assist Rolls-Royce with shorter term technical challenges. At later stages of technology development (TRL 5–6), Rolls-Royce interacts extensively with Advanced Manufacturing Centres to validate innovative ideas at a scale close to an operational environment, and to develop the manufacturing processes necessary to implement the new ideas efficiently at full scale. At the final stages (TRL 7–9), investment in full-scale manufacturing capacity is carried out through programmes specific to each product.

Measuring the returns to investment in innovation

Investment in innovation is considered crucial by Rolls-Royce in maintaining its position on the market. Choices around how to invest are driven by very long-term (40 to 50 years) business plans that set out the expected costs and benefits of developing a new final product – a new engine. Getting to the final product involves initially investing in a range of technologies, because of the complexity of the product, and with a view to mitigating the risk associated with specific innovations which may fail to reach the market. It is then very hard to disentangle the contribution of a specific investment to the development of a product and finally to an economic return. Specifically:

- At the moment of writing a business case for the development of a new product, there may be underpinning research that has already been carried out on specific technologies;
- Even if it is possible to link specific aspects of the performance of an engine to a specific technological innovation, it is not possible to link a specific aspect of the engine's performance to an expected rate of return. This is because Rolls-Royce's customers will value the final product as a whole in making their engine choices, rather than, for example, a specific reduction in weight that has been allowed by a certain technology;
- The strategy for investing in research and innovation is defined at the macro level, rather than at the level of a technology, or disentangling investment into capital and other components.

Interactions with publicly-funded investments

The rationale for public investment in innovation for aerospace

Public investment in research and innovation is considered crucial in supporting the development of technology in aerospace. At the initial stage of the development of a technology, this is due to the uncertainty involved and the long lags to gaining a return on investment. Therefore, public co-funding of investment mitigates risk and can potentially leverage private investment. At stages of the process that are closer to market, this is linked to the high costs involved in testing new technologies on larger scales, and the need to develop expertise that individual companies would not be able to sustain.

At the national level, Rolls-Royce stressed the importance of the continuity of public funding along the entire innovation process. While the availability of direct public funding is less important than the quality of the local research base, it can also influence decisions over the location of investment in R&D.

Interactions with academia: the UTC model

Rolls-Royce undertakes almost all its research into technology at early stages of development through its network of University Technology Centres (UTCs) – research centres located in leading universities in key research areas for aerospace engines. The network currently includes 31 UTCs, 19 of which are in the UK.

The first UTCs were set up in 1990, at Imperial College and Oxford University. This was the result of a conscious effort to provide structure to Rolls-Royce's increasing breadth of links with academia – essential to maintaining the firm's competitive advantage through involvement in cutting-edge research. It was perceived that concentrating effort into a small number of universities, each associated with a key research topic, would increase the effectiveness of the collaborations. This model would lead to longer-term relationships with universities, beneficial through increased stability of funding flows, exchange of staff and knowledge, and access to public funding.

Each UTC is led by a senior academic, and includes other academic and support staff, researchers, and doctoral students. Funding is provided through five-year rolling contracts, with the goal of developing long-term relationships. Specific research projects are funded through a combination of Rolls-Royce sponsorship and public sources, including Research Councils (notably the EPSRC), the Technology Strategy Board, regional agencies, learned societies, and EU institutions. In addition to financial support, Rolls-Royce provides in-kind support, including material, equipment, test facilities, access to data and experience, interaction with engineers and senior staff, co-supervision of PhDs, and training.

Within Rolls-Royce, interaction with each UTC occurs mainly through one of the firm's business units, which seek new technology for the development of the future generation of products to enter into service in the long-term (15 – 20 years from the initial research). As each UTC focuses on a specific technological area, a fundamental role for Rolls-Royce staff is to integrate progress from individual technology centres into the design and development of complex products.

Developing the Trent 900 swept wide-chord fan blade

The swept wide-chord fan blade used on the Trent 900 is an example of how the development of a new final product involves investment in a range of technologies. Bringing a single large component of the engine to market, in this case, required research undertaken at six distinct UTCs.

The Trent 900 is the fourth member of the Trent family, developed for the Airbus A380, and entered into service with Singapore Airlines in 2007.

This engine features the widest of all the fan blades on Rolls-Royce engines in service. Variants of the wide-chord design are found on all the Rolls-Royce large gas turbines, including the Trent XWB and the Trent 1000, which will power large civil aircraft for the next several decades. The development of the Trent 900 blade is part of a very long term evolution of fan blades from the relatively simple designs seen on engines in service in the 1970's, such as the Rolls-Royce RB211, to the highly complex designs seen today. This evolution has involved private and public sector investment from a variety of sources. Within this, it is possible to identify six key research streams undertaken at Rolls-Royce UTCs:

- the Materials UTC at Birmingham provided the necessary understanding of the behaviour of the material used for the fan blade using fracture mechanics;
- the UTC for Computational Engineering at Southampton studied the flow effects on fan noise, developing a component aimed at reducing the engine's emissions;
- the Cambridge UTC developed a range of aerodynamic models to increase the efficiency of the fan;
- the Solid Mechanics UTC at Oxford researched how to design the blade to ensure resistance to damage from foreign objects;
- the Imperial College London UTC carried out complementary research on the aero-mechanics of damaged fans, and;
- the Manufacturing Technology UTC at Nottingham delivered innovative tooling concepts to support the efficiency of the blade production process.

The initial research provided by the UTCs was integrated by a large in-house Rolls-Royce team in the final design of the blade. Significant additional investment by Rolls-Royce was required to develop the manufacturing capability for the production of the blade, including interaction with the Advanced Manufacturing Research Centres.

The development of long-term relationships with academia is perceived to provide significant benefits:

- Collaborations and related funding flows have greater stability. This gives researchers confidence that they are going to have the ability to bring their research projects to conclusion.
- The quality of interaction increases as a result of greater mutual understanding. Academic researchers benefit from the exposure to

technical challenges faced by Rolls-Royce, and, on the other hand, continued interaction with academia enables the firm to develop its capacity to absorb new ideas and solutions surfacing in academic research.

- Stable presence in universities improves access to human capital. Rolls-Royce supports well over 800 staff and PhD students in the UTC network. Out of the roughly 100 PhD candidates completing their studies each year, 25% are directly employed by Rolls-Royce, and a further 25% continue to interact with Rolls-Royce through their academic research.

The strength of the links between the company and its UTCs is further enhanced by temporary staff exchanges, through which academics join Rolls-Royce as industrial fellows, and Rolls-Royce staff members are seconded to universities. Within this scheme, staff members have received funding for collaborative projects through a number of schemes, including Royal Society Industrial Fellowships.

Interaction with publicly-funded facilities

Rolls-Royce highlighted the importance of public investment in innovation at the industrialisation stage of development (TRL 5-6), where testing starts to take place outside of laboratories, on a larger scale, with increased costs.

Advanced Research Centres, including the National Composites Centre and the Advanced Manufacturing Research Centre, are considered to be extremely important for allowing innovation in processes, business models, and testing in a representative environment:

- It is expensive to invest in production capacity. Once production capacity is set up, it is expensive to disrupt production to test innovations.
- Although universities are increasingly prepared to invest in facilities to attract expertise and funding, their resources are not sufficient to develop capability at this scale.
- Concentrating resources in a small number of centres has a positive effect on their quality. This is because it avoids the risk of dispersing resources among a larger number of smaller-scale facilities, and it improves the quality of the research undertaken by allowing researchers to be exposed to a wider range of issues.

This is also perceived to be a model that could be "exported" to other countries – supporting the development of similar research centres abroad as a way of stimulating trade with the UK.

Although large testing facilities are considered vital in supporting technological development and innovation in manufacturing processes, public investments of this type can only be successful where there has been a consistent effort over time to build up a certain type of capabilities. Rolls-Royce provided the example of successful testing facilities at the German Aerospace Centre (DLR) and at NASA that would not be worth replicating elsewhere because of their strength arising from consistent investment in the past.

Perceived barriers to engagement with the public sector

Having exerted a significant effort towards the creation of a network of key collaborations, Rolls-Royce is able to engage extensively with the public sector in the UK. However, there are areas where it was felt that policy could take action to determine further improvement, particularly in the ability of small and medium enterprises to interact with the public sector.

The Aerospace Technology Institute and the institution of the Advanced Manufacturing Research Centres have been important steps towards achieving coordination of public funding of science across different public bodies. This model could be extended to also include investment in academic research. The absence of an explicit link between the ATI and the Research Councils, however, was seen as a potential barrier to the continuity and stability of support.

Similarly, increased coordination of investment at the academic level would avoid fragmentation of expertise and potential duplication of facilities across universities. A successful example of coordination is the Materials Strategic Partnership, co-funded by the EPSRC and Rolls-Royce. Under the Partnership, Birmingham, Cambridge Swansea, and Oxford universities among others have a joint programme of research and support, aimed at extending the capability of existing high temperature metallic systems and developing novel alloys. The programme also involves key supply chain firms, such as TIMET, a leading producer of commercial titanium products. Initiatives of this type are beneficial particularly to small and medium enterprises, which do not necessarily have the resources to identify which institutions they could engage with productively.

Engagement with academia could also be facilitated by influencing the incentives that academic researchers are faced with. Although the current university evaluation process was placing greater emphasis on non-academic impact, including through industrial collaborations, it still relies heavily on publications. Moreover, the process through which universities are required to document their industrial collaborations can be onerous for firms.

4.4 Case study sector: Life Sciences

4.4.1 Sector background

Life Sciences are recognised as a key industrial sector for the UK, with a specific strategy published in 2011 which aimed to implement specific measures to encourage innovation and growth in the sector.[71] These included public investments; collaboration between industry, government and academia; increasing the efficiency of regulatory processes; and exploring how the NHS could better support the sector through data and research.

Table 11. Overview of UK Life Sciences sector (2013)

Sub-sector	Description	Estimated no. of UK firms	Estimated annual turnover	Estimated UK employees
Pharmaceuticals	Design, development and manufacture of pharmaceutical products and medicaments	477	£29.3 billion	70,310
Medical biotechnology	Invention, development and production of therapies based on biological processes	1,073	£4.2 billion	26,941
Industrial biotechnology	Application of biotechnology for industrial purposes, e.g. chemical manufacture and biofuels	121	£0.6 billion	1,787
Medical technology	Development and manufacture of non-pharmaceutical medical devices	3,309	£17.6 billion	76,723

Source: HM Government (2014), *Strength and Opportunity 2013: The Landscape of the Medical Technology, Medical Biotechnology, Industrial Biotechnology and Pharmaceutical Sectors in the UK* (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/298819/bis-14-p90-strength-opportunity-2013.pdf)

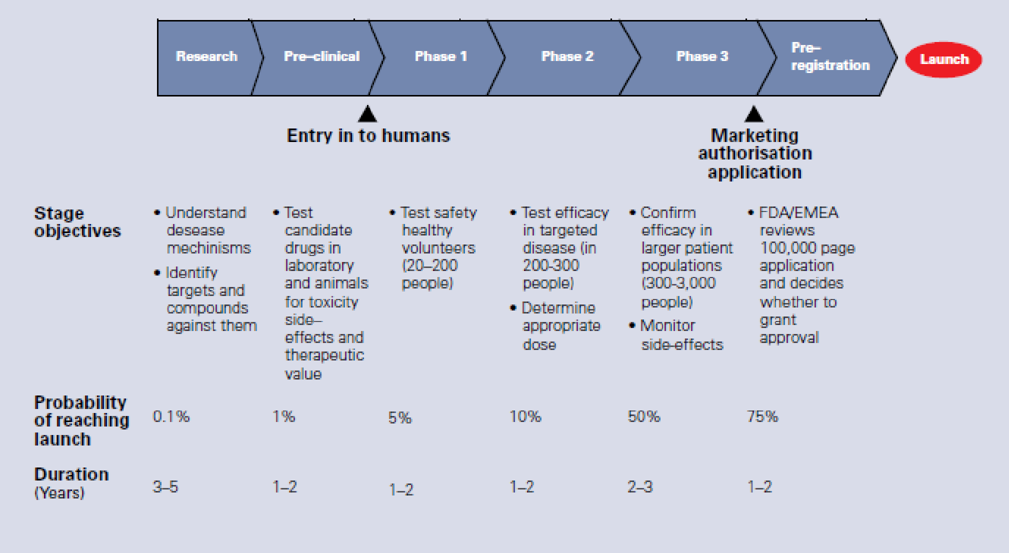
The Life Sciences sector comprises four key subsectors: pharmaceuticals, medical biotechnology, industrial biotechnology and medical technology. **Table 11** summarises evidence on the size of each sector in the UK.

The pharmaceuticals industry, the largest subsector by turnover, is known to be characterised by long lag times in developing new drugs. A formal multi-phase clinical trials process to test potential new drugs on human patients and monitor potential side effects can take 4 to 7 years with an additional 1 to 2 years for regulatory approval to be given for the drug to be taken to market. Prior to clinical testing, there is lengthy period of research in basic biology and the mechanisms of disease which helps to identify possible treatments, and a pre-

[71] BIS and Office for Life Sciences (2011), *Strategy for UK Life Sciences* (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/32457/11-1429-strategy-for-uk-life-sciences.pdf)

clinical phase where these candidates are tested in laboratories and on animal subjects. **Figure 18** shows an overview of the process.

Figure 18. Overview of development process for new drugs



Source: BIS (2010), *Life Sciences in the UK – Economic Analysis and Evidence for 'Life Sciences 2010: Delivering the Blueprint'*.

There is a well-recognised role for academia in this process, in particular the underpinning research. Lincker et al. (2014), for example, estimate that around 17% of new medicines in the EU between 2010 and 2012 were originated by academic or public bodies, including through public-private partnerships.

4.4.2 Case study 3: GlaxoSmithKline (GSK)

Company background

GSK is a global healthcare company, with commercial operations in more than 150 countries. GSK employs approximately 99,000 people worldwide, including approximately 39,000 in Europe.

The company had a total global turnover in 2013 of around £26.5 billion from three main divisions:

- Pharmaceuticals (67% of turnover);
- Consumer healthcare (20% of turnover);
- Vaccines (13% of turnover).

In 2013, GSK spent around £3.4 billion on core R&D, of which around £2.8 billion was spent on pharmaceuticals research. GSK has major research facilities in the UK (based at Stevenage, Harlow, Ware and Weybridge) as well as in the

USA, China, Spain, France, Japan and Belgium. Around 13,000 employees work for GSK in the UK, and around 30% of R&D investments are made in the UK, estimated to support around 3,700 jobs.

Case study summary of key findings

- Successful new drugs can receive patents lasting 20 years, though the effective patent life is shorter since patents are filed before drugs come to market. Post-patent, private returns can fall significantly though the returns profile will depend on the nature of the market at that point.
- Policies which helped to reduce development time would stimulate additional private R&D investment. One example would be the successful (though careful) use of patient-level data in the UK to help conduct clinical trials.
- GSK estimate their overall internal rate of return to R&D investments to be around 13%, though measuring the economic returns to a single investment or particular type of investment is extremely difficult.
- The quality of the science base is a key driver of where GSK locates research globally, though high quality science needs to go with a clear unmet medical need, potential for new drugs and a clear regulatory framework in determining what GSK invests in and where. R&D tax credits are not thought to drive where investment is located, but the patent box is seen as more critical.
- The industry has seen a recent move towards more collaboration and external engagement to drive innovation, recognising the need to absorb the advances in global understanding of basic science more effectively and the increased costs of the development of new treatments.
- GSK has moved away from simply giving grants to academics towards a partnership-based approach, which involves significant in-kind support as well as financing. Benefits of academic collaboration include increased capacity to absorb knowledge, innovative and challenging thinking from external voices, the potential to leverage additional private and public funding, risk sharing, opportunities to recruit skilled staff and developing networks.
- Potential barriers to academic engagement include a lack of commercial expertise amongst academics, a sense that academic expertise may be spread thinly across a large number of institutions, excess emphasis on IP and other measurable outcomes from collaboration, and perceived risks to publication.
- The relationship between academics and smaller biotech companies was also thought to be relatively poorly developed. The emergence of biotechs was seen to have disrupted the innovation process in the life sciences sector, with companies being formed on the back of sometimes quite 'old' science but with new understanding of their clinical potential.

Innovation at GSK

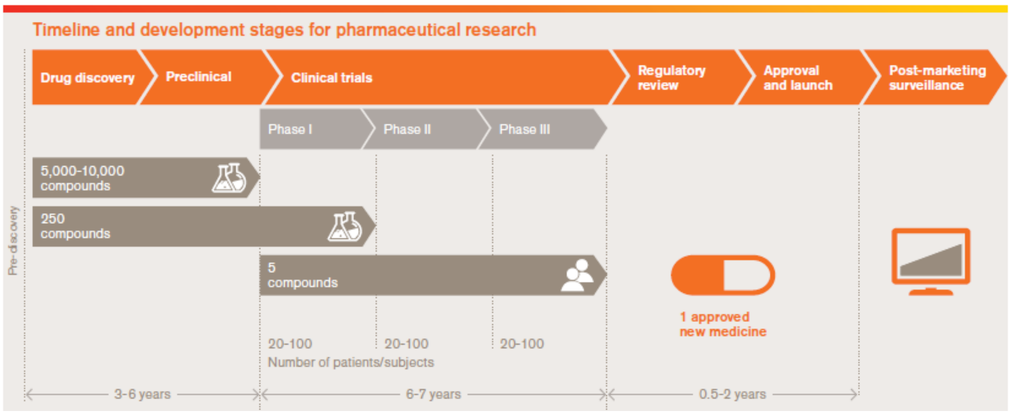
The innovation process

Continued innovation is considered to be essential for the success of life sciences companies like GSK. Developing new medicines and getting approval to take them to market is a lengthy, on-going and risky process. In recent years, there has been an increasing focus on developing new medicines which are strongly differentiated from existing therapies and which address areas of unmet medical need.

Research and development for a new medicine at GSK typically take at least 10 years and total investments of more than a billion US dollars, though there is clearly variation from case to case and the figures can be significantly higher. Of total global R&D investments in 2012 of £3.4 billion or so, more than three quarters (£2.8 billion) was invested in pharmaceutical R&D.

As noted in the sector overview, the development process includes a significant stage before clinical trials, consisting of drug discovery and laboratory testing. This can take 6 years or more before clinical trials begin. Only a small fraction of possible compounds (250 or so from more than 5,000) are typically taken to clinical trial, and a very small fraction of these (5 or so) will complete the clinical trial phase before being taken to regulatory review. Clinical trials can take another 6 or 7 years, or even longer, with up to 2 more years for regulatory approval and product launch. A summary of the typical process is shown in **Figure 19**.

Figure 19. Timeline for development of new drugs at GSK

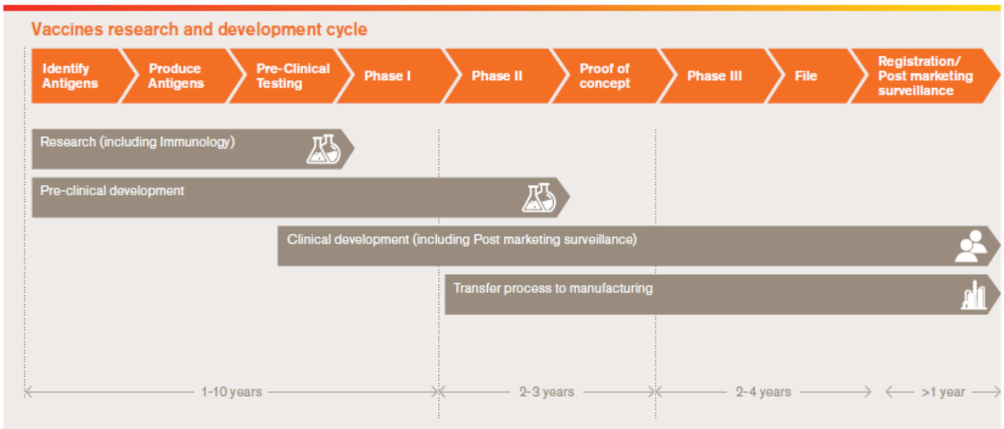


Source: GSK Annual Report 2013

It is also important to bear in mind that underpinning all of this is the pre-discovery, basic biological research, much of which is conducted in the academic institutions with whom GSK collaborates. Of GSK's total pharmaceutical R&D investments, around 28% goes towards the discovery phase, 59% to the pre-clinical and clinical phase, and 13% to facilities and central R&D support.

For new vaccines (which accounted for around 14% of R&D investments in 2012), there is a similar process of development from pre-clinical phases through to clinical development and ultimate approval and manufacture of the vaccine. This again is a lengthy process, with considerable variation in the length of development in individual cases (particularly around the earlier, pre-clinical and early-clinical phases). A summary is given in **Figure 20**.

Figure 20. Timeline for development of a new vaccine at GSK



Source: GSK Annual Report 2013

The lengthy time profile to develop new drugs in life sciences was compared to other sectors including aerospace which are also characterised by lengthy development periods for new aircraft. However, two key differences with a sector like aerospace were identified, which were thought to increase risks:

- More of the development process is internal to the company rather than components being licensed from a supply chain (and where the suppliers could potentially be changed if they fail to deliver and innovate as required to produce a new aircraft).
- There is less focus on 'technologies' with multiple applications: if a molecule being developed for a particular drug fails, it cannot always be considered for any other application.

The lifespan of a new drug in terms of delivering financial returns is partly driven by the life of a patent. Whilst patents typically expire after 20 years, the 'effective' life can be somewhat shorter – up to around 14 years or so – because patents are granted before the drug comes to market.

The precise profile of returns during the patent will be context-specific depending on the effectiveness of the drug relative to competitors, the introduction of other competing drugs and so on; similarly, the extent to which returns decay rapidly after patent expiry will vary according to the ease and speed with which generic alternatives are made available.

Types of innovation and investments driving innovation

Whilst there is obviously a focus on new products and particularly new drugs as 'innovations' in the sector, GSK thinks of innovation more broadly, including new business systems and how they are financed, and innovations around 'patient management', helping doctors and health providers understand how and when to use particular new drugs and even researching issues around how patient's diet can help recovery when new GSK drugs are prescribed.

There has also been significant 'innovation' in the R&D process at GSK, in particular around how they organise internal research and their external collaborations; we discuss these in more detail below.

Besides scientific R&D as an investment driving innovation, other necessary investments made by GSK which helped them to innovate were identified as training of staff, capital spending on research facilities and production facilities, and investment in the *design and layout* of these facilities (e.g. to help encourage more collaborative working internally).

Measuring the returns to investment in innovation

The amount spent on R&D is not based on any straightforward formula such as a proportion of turnover or profit, but is rather based on a judgement about the necessary levels of investment based on the opportunities to develop new medicines.

GSK estimate an overall internal rate of return (IRR) to their R&D investments, which is currently around 13% with a longer-term target to increase this to 14%.[72] The IRR is the discount rate at which the sum of all future cash flow resulting from R&D investments is equal to the cost of investment. To estimate the IRR from their R&D activities, GSK compare the R&D costs of developing late-stage projects to the forecast profits of new products which receive regulatory approval and are sold to market. The costs of capital investments which helped to realise the returns are included in this figure, but it is not generally possible to distinguish the returns to capital and current R&D investments separately.

As discussed below, however, it is typically difficult to estimate the return to a specific R&D investment project (whether conducted in-house or collaboratively), which are more often judged against whether they deliver a discrete outcome or set of outcomes that help to drive forward the development of a new product in a particular area of scientific interest.

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[72] See GSK Annual Report 2013, available from http://www.gsk.com/content/dam/gsk/globals/documents/pdf/Annual-Report-2013.pdf.

Research at GSK

Research and development investments at GSK focus on particular therapy areas (TAs) such as respiratory, immuno-inflammation, dermatology, neurosciences, oncology and anti-infectives.

Drivers of research investment decisions

GSK strategy is to focus investment where there is scope to generate significant returns. The key drivers determining the focus of pharmaceutical research spending include:

- Unmet **medical needs**: where is demand for new drugs likely to be high?
- Likelihood of **regulatory approval** for new drugs that will reach patients.
- The quality of the **global science base** underpinning research.

Not all therapy areas will be researched in all of the key research facilities around the world: the Stevenage R&D facility, for example, focuses mainly on research into respiratory illnesses, immuno-inflammation and biopharmaceuticals.

Simply having a high quality science base is necessary but not sufficient to encourage R&D investment in a particular TA. Where new scientific advances are thought to open up new opportunities likely to lead to medical advances, then R&D investment in those areas will be increased (for example, the recent growth of biopharmaceutical research).

For example, some five years ago GSK refocused its investment in psychiatry and neuroscience research based on a review of the research ideas emerging in that field. At the time there was limited scientific opportunity compared with other therapy areas. Many of the company's research programmes in psychiatry were closed down or spun out to small start-ups. GSK's R&D site in China had at that time begun researching promising new approaches in neurosciences and this effort continues.

Decisions over the country in which to locate R&D in a particular TA are influenced by a number of factors. A strong influence is the strength of the local academic science base in that country, and how that aligns with the in-house scientific capability in different countries. The quality of the local science base is clearly strongly dependent on public investment in research and higher education, though it was also noted that ensuring a well-skilled workforce more broadly was important as well. The high quality of the UK science base was identified as a critical factor determining GSK's substantial R&D presence here. Other factors include the time required to set up new R&D collaborations or the establishment of new facilities in a particular country, including negotiation periods with any public partners. A high quality science base may not be enough if there is a lengthy approval and regulatory process before new facilities or investments could be made.

Decisions over where to locate *within* a country are influenced by local factors such as the location of particular academic expertise, the quality of local infrastructure and transport connections, and so on. For example, GSK's Stevenage facility is well connected to London, Oxford and Cambridge through rail and road links; this high concentration of science expertise within a small geographic 'cluster' continues to be seen to be important in allowing for easy interaction between GSK and academia, including the specialist research hospitals in London and the Greater South East.

Fiscal incentives for R&D investment such as tax credits were seen as helpful in determining where R&D investments were located, but the presence of a world-leading science base was considered paramount. However, the UK Patent Box initiative (reduced rates of corporate tax for income derived from intellectual property) was seen to be potentially very important and was already having an influence on location decisions.

To some extent, as well, location choices are influenced by historical precedent: some of the companies which merged to form GSK in 2000 (and which had previously merged to form those companies) had traditionally been located in the UK for example.

In general, though, location was thought to be a more crucial strategic decision in terms of manufacturing facilities than in terms of R&D operations, given the (relative) ease with which ideas can cross borders. Nor was it felt to be necessary to have an R&D presence in a particular country in order to be able to sell products there: for example, while Germany is a big market for GSK's products, it conducts relatively little non-clinical R&D there.

Internal research processes

GSK's internal research process has changed fundamentally in the last five years or so. Increasingly, in recent years, the cost of developing new drugs has been rising and success rates have been falling across the industry; this has led to a renewed focus on the efficiency of the development process and finding ways to develop drugs more cheaply.

As a result of this, two key developments have been:

1. **Repersonalising** R&D to put decision-making in the hands of those with the scientific expertise and knowledge and;
2. Increasing **collaboration with external partners** (academia, SMEs and other pharmaceutical companies).

We return to issues around collaboration below, and focus on the changes to the research process more broadly here.

Research at GSK is now focused on small teams called Discovery Performance Units (DPUs). A DPU comprises a team of between 5 and 70 scientists (typically around 30 to 40) focused on a particular area of science or disease pathway.

There may be a number of DPUs working within a particular therapy area. GSK had a total of around 40 DPUs in 2013.

The DPU is tasked to discover and develop potential new medicines through to the early clinical trial stage (Phase II), and so focus explicitly on early-stage R&D. DPUs have a budget and prepare business plans which are reviewed by a Discovery Investment Board, whose members include senior GSK staff and external experts. The intention is the DPUs are able to demonstrate success within around 3 years in order to continue to receive research funding; the turnover rate of DPUs is approximately 10% or so. This creates an internal competitive process (within and between TAs) for GSK funding. Those working on unsuccessful DPUs will be reassigned to other research areas and activities.

The success of DPUs is judged against whether they have delivered on their plans (or at least are on a clear course to do so), rather than on a formal estimate of the 'returns' to the investment. Of course the plans themselves have to be evaluated upfront which includes at least some judgement on whether what might be delivered justifies the costs. The whole evaluation and judgement process is not fully metrics-driven, given the obvious uncertainties involved in the development process in pharmaceuticals.

DPUs are regularly challenged to propose the research activities necessary to advance the development process in their area of science, based on the latest evidence and research, gaps in knowledge which require original evidence and continued monitoring of potential external collaborators. New DPUs can be created if there is a demonstrable need, on the basis of initial funding for a 'pre-DPU' group which is used to prove the case.

Ideas underpinning new or existing DPUs are proposed by the scientists involved, and can be stimulated from knowledge of academic literature, participation at conferences or wider networks, and so on. All DPUs include at least some aspect of academic collaboration (this is discussed more generally below), and many devote a considerable amount of their budget to academic collaboration.

Interaction with publicly-funded investments

Recent years have seen a growing recognition that it is increasingly difficult for any single company to retain the capabilities needed for the whole R&D process entirely in-house. This is driven by a number of factors:

- the breadth of different areas of innovation in terms of new drug development;
- the increasing costs of bringing new products to market;
- a growing recognition of an increasingly large global science base.

As a result, GSK has begun to collaborate significantly more with external groups to drive innovation. This includes collaboration with academics, other large pharmaceutical companies and smaller companies (particularly biotechnology companies). This 'externalisation' was seen to be a key part of GSK's strategy around research and innovation, and the extent to which public investments were seen to support collaboration was thought to be important in determining where in the world private R&D investments were made.

The importance of public investments

Overall it was felt that direct public investments in supporting innovation in the life science sector were a small but important part of the development process, though with a recognition that public funding supports a lot of critical infrastructure (both physical, such as transport networks, and human, such as the skills of the science base) which is needed for private investments to take place.

Given the long development timeline for new medicines and the high risks and costs involved, there was a clear view that public investments which help to speed up the development process would be hugely important, both in determining where private investments took place and the total amount of private investment. Reducing development times would increase the return on GSK's own investment, and so not just affect location but also (given the point raised earlier that R&D spending was not driven by any simple formula) leverage additional private investments. A number of opportunities for public investments which might reduce development times were identified, including the data infrastructure around electronic patient records, investments in clinical methodology, and developing the skills of clinicians to translate underpinning theoretical research into opportunities that can be commercialised.

Interactions with academia

The relationship between (large) pharmaceutical companies and academia was felt to be well-established, with a mutual understanding of needs and the strengths that could be brought to bear through collaboration. Collaborative agreements with academic institutions vary in scope, from small data-sharing arrangements (which may not include any financial component), through to multi-million dollar research contracts. Whilst GSK is a significant investor in academic research in terms of funding, non-financial support in kind, in terms of data, technology and access to know-how was felt to be even more significant.

There was a perception that the nature of academic collaboration has changed in recent years, moving away from a model where a company would give grants to academics to deliver particular results, towards a partnership-based approach where both GSK and the academic partner bring particular skills to tackling an identified commercial need. From GSK, for example, this can include data-sharing (including clinical trials data) with academics, providing access to platform technologies or molecules, and commercial know-how. An increasing move towards open data is a way that this can be demonstrated: for example, in 2010 GSK deposited scientific information on over 13,500 possible compounds which could be effective against malaria with the European Bioinformatics Institute; these data could be used freely by academics and others.[73]

In part, this reflects increased competition for collaboration with the best academic scientists with a number of companies obviously keen to work with them. For these academics, the value of collaboration is not funding, but the quality and impact of any resulting publications.

GSK's current academic collaboration

At present, GSK's collaborations include more than 500 active collaborations with more than 50 UK Universities; collaborations in many other European countries, the largest number in Germany, France, Switzerland and Ireland; and agreements in 23 US states, focused most heavily in North Carolina, Pennsylvania, Massachusetts and New York.

As well as collaborations with institutions, GSK also co-funds around 240 PhD students in the UK, mostly in partnership with three key Research Councils (the BBSRC, EPSRC and MRC). Over 30 new studentships co-funded with Research Councils were formed in 2013.

Support is also given to earlier-stage students, with 310 undergraduates taking part in an industrial placement at one of GSK's UK facilities (mostly their Stevenage and Brentford sites) in 2013.

This investment in studentships is seen to be an important innovation investment by GSK, ensuring the quality of the future science base which will be needed to develop new medicines and other medical products in the future. Students are potential recruits for the company in the future, and also help (by working jointly with an academic and industrial supervisor) to provide links to university departments as a way for new academic collaborations to be developed or existing relationships to be strengthened.

A number of benefits from academic collaboration for GSK are identified, including:

- The ability to access the widest possible, high-quality scientific research, including the latest knowledge in terms of basic biological understanding;
- Access to innovative thinking and challenge from people who are not embedded within the industry;

[73] See Gamo, F-J. et al. (2010), 'Thousands of chemical starting points for antimalarial lead identification', *Nature*, 465, 305–10

- Access to academic materials and resources and an improved ability to 'absorb' academic know-how to help answer specific research questions;
- More immediate access to capabilities and resources than would be possible in trying to develop new expertise within GSK internally;
- The ability to leverage other sources of public and private investment in driving forward innovation;
- A sharing of risks and rewards associated with pharmaceutical research;
- An ability to build links for future collaboration at a global level, and;
- A potential pathway to recruiting high-quality staff.

Academic collaboration does not fundamentally alter the direction of GSK's research: the broad areas of research interest, as noted above, are determined by a combination of clinical need, scientific knowledge and regulatory approval. Collaboration does allow for greater access to the knowledge and scientific expertise which effectively complements the in-house research which GSK conducts in specific areas. The underpinning science gives GSK confidence to invest in developing new drugs through the full development process.

None of GSK's collaborative work is purely 'blue sky' basic research, but having the ability to work with experts in the underpinning science around biological processes was seen to be critical in giving GSK the confidence to invest in the rest of the development process. In this sense, then, investment in the underlying science base helps to leverage private investment which develops products which can be commercialised.

While there has been a drive towards increased academic collaboration coming from within GSK, there is also a sense there is an increased demand for collaboration from the academic sector as well in the UK. This was thought to come to a large degree from the new Research Excellence Framework (REF) assessment process, which allocates 20% of the overall result to the non-academic impact of university research, and an increased emphasis on impact as part of the research council funding process.

Being able to demonstrate impact in terms of contributing directly to the development of a new drug, or a new molecule which in future could form the basis of new drugs, was therefore valuable. Similarly, Research Councils were also thought to be encouraging collaboration through co-funded calls for proposals with industry, which also helps the Councils demonstrate the impact of their investments.

Successful academic collaboration was thought to require a number of components, besides financial resources and a willingness to engage and communicate effectively on both sides. These include:

- A clearly defined need for the collaboration from GSK, whether the clinical and scientific capabilities of the academic collaborators, or access to data, technology or patient populations which GSK lacks;
- A clear programme of research with well-defined scientific milestones, a clear workplan and agreed deliverables, and;
- Increasingly, a move towards identifying criteria against which the success (or otherwise) of the collaboration will be judged. These criteria can include agreed cut-off points to terminate collaborations early if results are not being produced as hoped, though this tends to be rare.

This framework is seen to be necessary for smaller as well as larger collaborations.

Judging the success of collaboration

Assessing the value of collaboration is difficult to do quantitatively, but in biopharmaceuticals GSK is trialling a system to assess the value of each academic collaboration and evaluation by looking at the deliverables, the original success criteria in the work plan and the ability of the research to affect the strategic direction of internal programmes. This is a subjective assessment but could be used to drive biopharmaceuticals to focus their future collaborations to particular types of research programmes and certain institutions.

A number of different models to develop academic collaboration have been developed by GSK. For example, one of their R&D facilities at Tres Cantos in Spain includes a significant **'open laboratory'** component where academic researchers can apply to work alongside GSK scientists on issues around diseases in the developing world. This does not have specific additional public investments to support it, but is seen by GSK to be useful to help academic researchers understand the needs of the industry, and represents leveraged in-kind support from GSK in terms of facilities and resources alongside the publicly-funded investments in the academic researchers themselves.

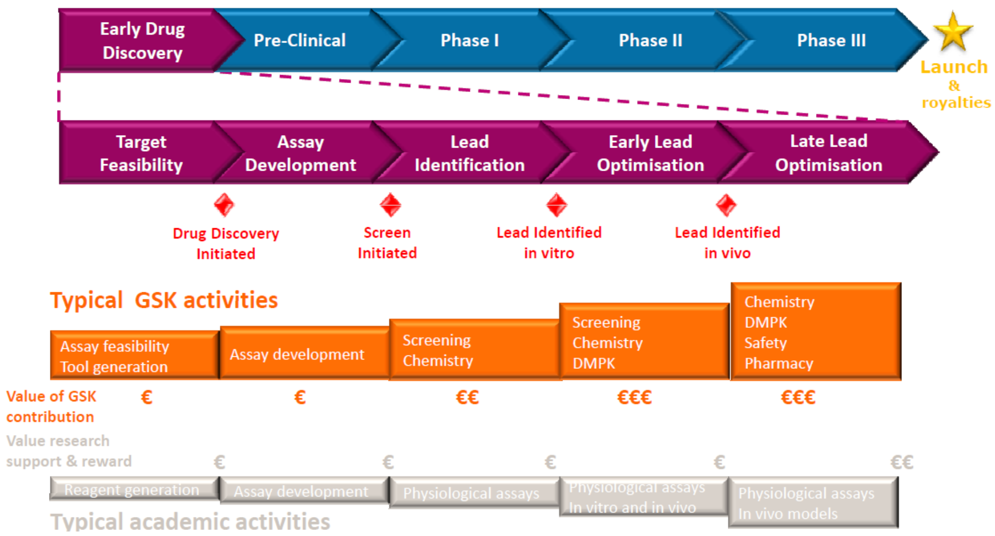
The main recent innovation in academic collaboration is the **Discovery Partnerships with Academia (DPAc)** model. This began around three years ago. Recognising that important insights into biology and the clinical aspects of disease relevant to particular TAs lie within academia, but also that academics are not always able to translate that knowledge into new medical products, DPAc partnerships are seen as a model to bring together GSK's drug discovery expertise with the academic knowledge. Worldwide, there are 11 active DPAc partnerships in place at the moment, including a number in the UK.

The academics involved are those seen to have knowledge and expertise which are essential to developing the product, where this knowledge is not readily available elsewhere, and the projects are those which ex ante are thought to have a reasonable likelihood of success on the basis of a clear therapeutic and scientific hypothesis, and an expectation that there is a reasonable opportunity to generate a molecule and carry out effective clinical evaluation.

The focus of DPAc partnerships is on developing new drugs through the early drug discovery phase, although the GSK-Academic partnership continues through to the final medicine being launched.. The academic involved will then receive a royalty .The idea is that having a single partnership across the development process, with a clear role for all parties involved, would increase the likelihood of success.

The precise start point can vary according to the facilities and expertise available at a particular academic institution, but is always after the point where a specific target for a potential new drug has been identified (that is, funding is not given for purely exploratory research). The typical resource costs to GSK, and the value of the funding to the academic, increase through the discovery phase (see **Figure 21**).

Figure 21. Early stage development through DPAcs



Source: GSK Presentation Material

The approach is not centred on creating infrastructure such as open laboratories where GSK and academic researchers are co-located; rather, DPAc partnerships involve joint research projects involving GSK scientists and an academic or academic research group and activities which take place both at GSK facilities and the academic institution. An academic Principal Investigator and a GSK drug discovery expert lead the projects together under an agreed framework.

The partnership includes access to GSK drug discovery capabilities for the academics, and helps to transfer insight and knowledge about the drug discovery process back into academic institutions. It is not about GSK funding academic research and licensing any discovery. Along the development process, the academic benefits from the generation of research tools and from jointly-authored research publications, though GSK reserve the right to patent any resultant molecules before publication takes place.

Joint projects are reviewed against milestones with decisions taken about whether to continue GSK's resource and funding to the next stage of development. Should a decision be made not to do so, the rights to selected molecules revert to the academic who is free to continue to progress the research themselves (or in collaboration with another commercial partner). Even where the DPAc partnership is terminated, however, there is value to both GSK and the academic in the contacts and networks which are created and reinforced (which can also spill across wider academic networks that the particular academic partner already has), and opportunity for further collaboration remains.

Discovery Partnerships: Dundee

GSK have had two DPAc collaborations with scientists at the University of Dundee, each beginning in 2011. One, headed by Professor Irwin McLean, focused on treatments for a rare genetic skin disease (Recessive Dystrophic Epidermolysis Bullosa) causing blistering under mild pressure. The other, headed by Professor Susann Schweiger, focuses on the genetic brain disorder Huntington's disease.

The McLean collaboration is no longer active, though under the terms of the DPAc model he was assigned the five most promising compounds developed at that point and is free to develop them further, as well as to use them as tools to further the understanding of the biology and the disease. The decision to stop the collaboration was taken jointly under a full appreciation that research investments in life sciences and drug development are risky and most will not be expected to succeed.

The initiation of the Dundee DPAc collaborations was facilitated by a long-standing relationship with Dundee. This includes a GSK involvement in a consortium comprising a number of pharmaceutical companies, the Medical Research Council and the University. The Division of Signal Transduction Therapy (DSTT) consortium has provided around £50 million of private investment to a number of research teams based at Dundee since 1998, and was renewed for a third time with a £14 million investment in 2012. The DSTT is working on new drug treatments for several diseases including cancer and arthritis, and includes regular knowledge exchange between the companies and the academics involved.

Links forged between GSK and Dundee through the DSTT helped the company identify possible DPAc collaborations through developing trusted relationships. Importantly, this was not just about academic links, but also experience of working on contractual issues with the University.

There are a number of ways in which potential academic collaboration opportunities are identified, though precisely how it is done is very case-specific. One route relies on pre-existing networks: a number of GSK's senior leaders have academic backgrounds. In other cases, internal GSK scientists will be able to identify leading academics in particular areas of science based on their own understanding of the scientific literature. Although not used in sourcing DPAc partnerships, another approach open to GSK researchers where they have less direct experience is to use external consultancy support to mine literature and data which in turn helps identify possible collaboration opportunities.

New DPAc partnerships are identified through a combination of advertising, direct approaches to Universities (often through Technology Transfer Offices), and through building on past links and collaborative activities. Where key further information is required to provide the confidence in the academic's innovative idea to initiate a full-blown DPAc partnership, a 'pre-DPAc' interaction can be initiated. A further means of identifying academic collaborative opportunities is the Discovery Fast-Track Challenge: successful applicants will gain access to screening their target of interest against GSK's compound collection. Successful projects may then get the opportunity to continue their collaboration with GSK under a DPAc collaboration, or have access to identified compounds to progress their research (subject to GSK's existing internal and external obligations).

In their UK biopharmaceutical research, GSK have recently established an innovation fund which is aimed at identifying academics as potential collaborators. This involves a seminar hosted by GSK which highlights what they can offer to collaborators in terms of resources (including access to GSK proprietary platform technology) and opportunities in biopharmaceutical research. This was taken originally to an academic meeting in Cambridge, and offers a 2-year funding stream to successful applicants who work for some time at a GSK facility and then at their own institution. This has now been rolled out across 11 institutions, based on the success of the initial collaboration with Cambridge.

However collaborations are not formed entirely because of GSK seeking them out actively: sometimes they are formed through academic approaches to GSK on the basis of the resources (financial and non-financial) that the company is apply to provide to any partnership.

Barriers to academic engagement

As noted, in general GSK has a good relationship with academia, but some barriers were identified which inhibit the ability to form good collaborations:

- A **lack of commercial expertise** which can lead academics to over-estimate the commercial value of their ideas or technologies;

- A need for **inter-university collaboration** to share equipment, technology and know-how to help develop a 'critical mass' of expertise in particular areas of science and avoid spreading knowledge too thinly;
- Over-emphasis among academics on **generating intellectual property** (e.g. filing patents) as a result of a collaboration, even if the IP is not actually valuable. This may be driven by a perception that this activity (along with e.g. spin-off companies) is a 'measurable' impact which can be evaluated, though this is perceived to be changing towards a move towards partnerships between industry, academia and government;
- Possible administrative and other **delays in being able to broker partnership agreements**, which can increase development times and so make collaboration much less attractive;
- Perceived risks to the **ability to publish** amongst academics (see below).

Joint authorship

In general, it was felt that a significant value of collaboration between GSK and academics in terms of joint working was to help academics understand commercial and business needs and how their research could be made more useful to meet those needs. However, it was thought to be easier for GSK staff to work in academic labs than vice-versa (notwithstanding the Spanish 'open laboratory' example outlined above). One barrier preventing industry secondment by academics in the UK was thought to be a negative impact on the academic's capacity to publish journal papers.

Highlighting the potential for joint-authored (GSK-academic) papers was therefore seen to be important as a way to incentivise academic collaboration. GSK argued that collaborative papers could be higher quality, at least as measured by citation, than papers authored by academic researchers along. Evidence from Marston (2011) finds that, across a number of developed countries including the UK, the relative citation impact of biomedical papers is higher for those which are published jointly between academia and business than those which are purely academic. The difference in citation impact between jointly-published papers and those published purely by corporate authors was most pronounced in the countries that publish the most papers (the US, Japan, UK and Germany).

GSK has published a significant number of co-authored papers in leading journals (more than 20 publications in Nature and the New England Journal of Medicine, for example, in 2012 alone). A number of papers have received a high number of citations and generated significant scientific impact, including for example pioneering work to synthesise the mouse genome, which now has almost 5,000 listed citations on Google Scholar.

Interactions with university spin-off companies

There was an increasing use of collaboration between GSK and other companies as a way to share both risk and reward in the sector. Models of new drug development in the industry had been changed in recent years with the emergence of the biotech sector in particular, with a large number of small, innovative companies spinning off from universities as the result of particular ideas generated from basic research and laboratory development. This was seen to have disrupted the innovation process for large pharmaceutical companies like GSK and spurred the recognition, described above, that the entire R&D process could not be taken forward entirely at in-house laboratories.

It was argued that the relationship between smaller pharmaceutical or biotech companies and the public science base was less well-developed. An area of concern, for example, was thought to be how small biotech companies (including those which are academic spin offs) could be supported and helped to grow, including through funding and ensuring the continued quality of the science within the company.

Drawing on academic spinoff companies: Domantis and GSK

Domantis was a university spin-off company set up in 2000, co-founded by two scientists from the MRC-funded Laboratory of Molecular Biology (LMB) at Cambridge. The company was working in the area of monoclonal antibody (mAb) therapies. mAbs are highly specific antibodies produced in the laboratory by a clonal cell line which can be used to neutralise disease-causing proteins, or bind to target cells as a way of stimulating the immune system to attack them.

At the time Domantis was established, mAbs were already being used successfully in developing new treatments, and one of the co-founders, Greg Winter, had led some of the pioneering research.

The innovation of Domantis was to build on the discovery that a small fraction of the antibody called the domain antibody (dAb), which is only around $1/13^{th}$ the size of the full antibody, could give many of the benefits of the full antibody as a class of potential medicines. The smaller antibody was useful as they could penetrate tissue more deeply and provide new formats for antibodies which could help develop them into new therapies. However dAbs had technical challenges which hindered their use in developing them into useful treatments; Domantis span off from work done by the founders to overcome these drawbacks.

The MRC licensed its patents for these kinds of domain antibodies to Domantis in return for a stake in the new company, and also provided initial seed funding through an MRC-associated venture capital fund. In 2001, additional investments were made by Peptech, a publicly-funded Australian venture capital company, in Domantis. In late 2006, GSK purchased Domantis for around £230 million, leading to a significant royalty payment (through the patents licensed) of over £7 million to the MRC.

The development work done by Domantis helped to validate dAbs as a potential source of new therapies. By the time GSK acquired Domantis, the company had raised US$83 million from investors and had 80 employees, including 73 in the UK, and was developing its own clinical capabilities. The acquisition came about through business development discussions carried out between Domantis and a number of pharmaceutical companies, including GSK. Domantis were keen to develop a strategic collaboration with GSK, and this pre-existing relationship, combined with a development in GSKs own strategy towards wanting to move into the biopharmaceutical space, helped set the acquisition process in place.

For GSK, the acquisition led to a number of benefits including:

- Access to technologies and ways of making medicines around dAbs;
- Access to Domantis's pipeline of therapies and patents;
- Access to the founders and other expert staff within the company.

Since the acquisition, and in line with the development of GSK's own research model described above, the work carried out by Domantis has been integrated into the DPU framework focusing on more disaggregated R&D carried out by smaller, focused units. The main Domantis building itself and a large number of people remain in Cambridge, which helps to maintain links with the university, though a number of key staff members are integrated into the main GSK facilities in Stevenage.

Research leading to the development of mAbs was carried out in the mid-1970s at the LMB in Cambridge, and dAbs were reported in 1989.[74] This demonstrates the lengthy time delays between academic discoveries funded through underpinning publicly-funded science and, in the case of dAbs, how they can be developed into potentially useful innovations from a commercial and social perspective.

Interactions with public science infrastructure investments

As well as academic collaboration, GSK regularly works with other UK and international funding agencies such as the Research Councils and third sector bodies such as the Wellcome Trust to leverage funding in areas of science where both sides have an interest. This is often done in a consortium arrangement with other companies in the life sciences sector.

It was felt that, particularly in the UK, there was keenness amongst the leadership of these funding agencies for collaboration and co-operation with industry, with

[74] See http://www2.mrc-lmb.cam.ac.uk/antibody/.

improvements to the translation of biomedical research into patient benefit being seen as a priority, and which had increased the top-down encouragement for such collaboration to occur.

GSK has also contributed financial and non-financial investment to large-scale facilities which have also received public support. For example, the Stevenage Bioscience Catalyst (SBC) is a £38 million open innovation partnership between private and public sectors, with government (BIS, the TSB and the former East of England Development Agency), the Wellcome Trust and GSK as founder partners. Of the initial £38 million cost, GSK provided around 30%. The aim is to provide small biotech and life sciences companies with access to the expertise, networks and scientific facilities traditionally associated with multinational pharmaceutical companies, and to facilitate a flow of ideas and knowledge exchange between tenants at the facility. This, it is hoped, will help academic ideas to be translated (through start-up biotech and other companies) into commercial outcomes. Tenants retain full independence and the freedom to interact with any commercial partners.

The SBC opened in 2012 in a bioscience park adjacent to GSK's R&D facilities in Stevenage. Geographical proximity and the 'clustering' effect were felt to be important ways in which the interaction between GSK and the occupants of the Catalyst could be made most productive, allowing new ideas and ways of working to be discussed and tried in a straightforward way.

Investing in early-stage biotechs through the SBC: Puridify Ltd.

One company at the SBC, Puridify Ltd., is a biotech spin-off from the Advanced Centre for Biochemical Engineering at UCL.[75] The company is developing a resin to improve the efficiency of purification in the manufacture of biotherapeutic products (therapies developed from living organisms), based on an STFC co-funded grant which supported the doctoral work of one of the company founders. Puridify won a competition sponsored by GSK's venture capital arm, SROne, in 2013 which included investment of £100,000 and a year's occupancy at the SBC. The company has further benefitted from investment of £168,000 from the Technology Strategy Board's Smart award scheme to develop the proof of concept.[76] Other than the venture capital investment, GSK have not provided further direct financial support, but have provided pre-competitive investment in-kind to support the TSB investment, including access to manufacturing know-how and materials, facilitated by the company's presence at the SBC.

At this stage, the technology being developed by Puridify is not of immediate benefit to GSK commercially, but the potential for the product in the future

75 http://puridify.com/

76 https://www.innovateuk.org/-/smart

meant there were incentives for GSK to provide additional in-kind support to help it be developed and assessed appropriately, potentially enabling the company to access the resin in the future

Public investments in patient data infrastructure are also thought to be an important area of future benefit for companies like GSK. For example, the further development of electronic patient health records could improve the UK's infrastructure for clinical research investment by the sector, leading to enhanced patient benefit through improved patient enrolment into clinical trials and better safety monitoring (pharmacovigilance). .There is however a full appreciation of the need to address concerns around data security and data misuse, the need for clear protections to be put in place and the importance of having systems in place to ensure the data are collected accurately.

There was a sense that countries that were able to develop this data infrastructure successfully would see increased investment and collaboration from the private sector as a result.

4.4.3 Case study 4: Johnson & Johnson

Company background

Johnson & Johnson (J&J) are a family of companies operating in over 60 countries worldwide, employing 128,100 people globally in 2013. Total global sales that year were $71.3 billion, split across three key divisions: pharmaceuticals, medical devices and diagnostics (medical technology other than medicines), and consumer products. In terms of pharmaceuticals, the company focuses on four key areas: immunology, neuroscience, oncology and infectious disease.

The company invests substantial amounts in R&D: $8.2 billion in 2013, or 11.5% of total sales. **Table 12** below shows sales and R&D spending across the three key divisions.

Whilst medical devices are a slightly larger share of total sales, in terms of R&D, pharmaceuticals is by far the largest division. R&D costs include investments in discovering, testing and developing new products (including regulatory compliance), as well as improving existing products.

Table 12. J&J financial information, 2013 (global figures)

Division	Turnover (USD, billion)	R&D (USD, billion)	R&D as % of turnover
Pharmaceuticals	28.1	5.8	20.7%
Medical devices and diagnostics	28.5	1.8	6.3%
Consumer	14.7	0.6	4.0%
TOTAL	**71.3**	**8.2**	**11.5%**

Source: J&J 2013 annual report (http://2013annualreport.jnj.com/)

Case study summary of key findings

- Innovation is critical to the company: around 25% of J&J's pharmaceutical revenues stem from products launched within the last five years. External collaboration with academics and other companies is a key driver of innovation – half of new approvals in recent years were based on assets discovered outside of a J&J research lab.
- Public funding was a strong influence on where J&J located research activities to the extent that public investments produced a strong national or regional science base, and helped foster a collaborative and entrepreneurial attitude amongst academics.
- It was thought to be relatively easy for large companies like J&J with significant internal scientific expertise to identify opportunities for academic collaboration, and there was a perceived willingness among academics to engage.
- J&J have recently innovated in their early stage research and development process, opening a small number of 'Innovation Centers' in four locations, including London. These bring together scientific, financial and legal experts to help facilitate collaboration, similar to a business incubator model.
- The choice to open a Center in London was driven largely by the quality of the clinical and academic science research base in the South East, transport connections, access to private and public finance and a willingness to collaborate.
- It will take time to know whether the Centers have delivered significant new opportunities for produce innovation, but the potential returns to the model are seen to be if J&J can licence successful new products earlier in the development cycle rather than buying into later-stage innovations through acquisition. However it is expected to be difficult to attribute a particular 'rate of return' to the Innovation Centers themselves.

Research and innovation at J&J

Drivers of innovation and the direction of research

Innovation is critical to a company like J&J: around one quarter of the company's pharmaceutical revenues derive from products launched in the last five years. In turn, collaboration is seen as critical to innovation: around 50% of new drug approvals in the last five years at J&J were based on external research (where the asset was discovered outside of a J&J lab).

A broad driver of innovation investments for J&J is to try and deliver larger 'transformative' innovations, focusing on new drugs or products with the potential to have a major impact such as the development of new treatments to prevent Parkinson's or Alzheimer's, rather than on more incremental improvements to existing treatments.

The company focuses on core areas of expertise in terms of developing new pharmaceutical products, rather than trying to cover all possible clinical needs. These areas are determined on the basis of patient needs, the expertise of staff and existing collaborative networks, as well as the market opportunities to deliver transformational innovation.

Success at bringing new products through the development pipeline was thought to require:

- People with **deep expertise** in basic biological research and clinical research, who need to be brought together and connected across institutions and geographic locations;
- An openness to **networking and collaboration** to allow these connections to be made, ensuring that (rapidly-changing) developments in the underlying scientific knowledge could be quickly and flexibly translated into new opportunities for product development;
- Among academics, a **desire to translate** research into new treatments and drugs, and a willingness to invest time and resources to do so.

The returns to investment in R&D are not purely financial, particularly in areas like biomedical and health research. Rather, there are wider social returns from improving national health outcomes. These wider benefits were seen to be a driver of decisions even for a private company like J&J, but were clearly also identified as the key objectives which should underpin public investments in science rather than the potential for generating economic returns in the form of royalties and profits.

The role of public investments as a driver of private decisions

Direct public support in terms of finance was not seen to be a big driver in terms of where J&J locate their innovation expenditures, or the amount spent, though the role of government in promoting entrepreneurship and helping to facilitate networking and collaboration, as well as of course in the basic underpinning expertise and human capital in academia, were identified as highly important with stronger potential to leverage and benefit from additional private investment.

Interaction with publicly-funded investments

Interactions with academia

Collaboration with academia is now focused on the Innovation Centers (see below), set up in the last year or so in four locations, as a way to tap into early-stage (pre-clinical) research.

Academics and researchers with whom J&J collaborate are identified on the basis of their academic record. There are thought to be only a small number of world-leading academic experts researching particular diseases or areas of relevant science and they can be relatively easily identified through their published research, conference attendance, links with internal scientific experts and so on. Universities were also thought now to be attuned to opportunities for collaboration with the private sector, and had set up effective internal processes to do so. The need for a separate publicly-funded body to help identify collaborators was therefore seen to be fairly limited.

In terms of collaboration, J&J seek to work with academics in areas which match the company's core competencies, such that the partnership can offer more than just financial support, but instead represent a genuine mutual opportunity to exchange knowledge to help innovate.

Perceived barriers to academic interaction

It was felt that whilst collaboration between academics and large companies like J&J was reasonably successful, there were still barriers at the interface between them in terms of a lengthy negotiation process to transfer IP know-how from the university to a biotech or a company like J&J. This can be a large part of what is already a lengthy development cycle.

Johnson and Johnson Innovation Centers

In late 2012, J&J announced plans to open four 'Innovation Centers'. The first opened in London in March 2013, followed by California and Boston in June 2013. A fourth is due to open in Shanghai later in 2014.

The Innovation Centers embody the idea of 'innovation in the innovation process', representing a new model for the company in translational research: that is, early-stage (before clinical proof-of-concept) development of new ideas being identified and then taken forward towards new products and new medicines.

Prior to the Innovation Centers, most of the company's senior scientific R&D leaders were located in Belgium, New Jersey and Pennsylvania. The move towards locating the Centers in London, Boston, California and Shanghai was based on moving scientific leaders to geographical proximity to areas identified as being highly innovative in life sciences, with an explicit objective for the Centers to become actively involved in those 'clusters' or 'hubs'. This was thought to simplify the process of collaboration, helping the company co-ordinate its collaborative activities with academics and biotech entrepreneurs. In the context of the development process for new drugs, the Centers could therefore help to reduce lag times in the research and pre-clinical phases.

Innovation Centers seek to identify the best early-stage innovative ideas coming from academia and biotech start-ups, and then develop collaborative ways of developing those ideas, bringing together J&J scientists (who are expert and active members of scientific communities), business, financial and legal experts and representatives from J&J's venture capital arm, Johnson & Johnson Development Corporation (JJDC) in the same office in order to do so. This is similar in structure to business incubators which bring business and financial expertise under the same roof to help develop innovative ideas, though the Innovation Centers also include the scientific knowledge to allow the medical potential for new ideas emerging from external sources to be evaluated properly.

The aim of the Centers is less about increasing the amount of capital being invested in R&D (whether by J&J or other collaborators), but rather to ensure that investments are made more efficiently and effectively in supporting the company's broader strategic goal to deliver more transformative innovation. The Centers focus on taking research ideas from laboratory benches to a proof-of-concept stage, which can take around 5 or 6 years.

The Centers are not focused only on pharmaceutical innovation, but also J&J's other key divisions of medical devices and diagnostics, and consumer products. A number of key priority areas within each division are identified,[77] and all are taken forward from within the Innovation Center by the teams there. Scientific experts from across different Therapy Areas and areas of business activity are all brought together into the same location as a key part of the Center. These are people with practical experience of discovering and developing drugs and other products and can bring that experience to bear in helping academics, clinicians and startup companies take their ideas forward.

The London Innovation Center

Within Europe, London was chosen as the location for an Innovation Center largely because of its status as part of a wider networked cluster of life sciences research in the South and East of England, including Oxford and Cambridge Universities and the University of London. J&J estimate that the Oxford-Cambridge-London 'triangle' contains 170 or so medical biotechnology

[77] See http://www.jnjinnovation.com/about-jnj-innovation/innovation-interest-areas.

companies, including university spin-offs and other start-ups as well as other large life sciences firms, and new developments such as the (publicly and charitably funded) Francis Crick Institute being built in London.

Seeing the as an integrated 'cluster' rather than a set of discrete institutions was thought to be critical. In a relatively small geographic space, London and the South East offers:

- High-quality academic research: 3 of the top 10 global universities;
- High-quality clinical research;
- A long-standing tradition of medical and biotech research;
- Evidence of entrepreneurship and willingness to take ideas from academia into product development;
- Financial support in terms of investment from private and public sectors;
- An openness between academics, clinical researchers and venture capital investors to work together;
- Support from government and local authorities.

Support from the public sector was seen to be important but not directly critical in the decision to locate the Center in London. More generally it was thought that there was a clear public commitment to the life science sector, evidenced by examples such as 'MedCity', which is investing money from the Higher Education Funding Council for England and the Mayor of London's Office to promote life sciences research and facilitate and attract private venture capital investment into biotech companies in the Greater London area.[78]

This proximity between J&J and the science base was seen to be important to drive innovation: the ability to interact frequently and build trusted and transparent relationships was seen as important, rather than simply working remotely. This was particularly important when the risks around innovation and experimentation to develop new products and medicines are so high – most collaborations will 'fail' in that they do not result in a new drug, but building a close relationship makes it easier to continue the partnership and try new approaches.

London was also seen to be well-connected with the rest of Europe, and so had the potential to act as a hub for early-stage innovation not just for the UK but the wider continent. Indeed, one of the earliest collaborations identified from the London Innovation Center in May 2013 was with three Belgian academic institutions and research centres,[79] focusing on early-stage innovation focused on neurodegenerative diseases including Alzheimer's, Huntington's and Parkinson's. This collaboration saw J&J (through their pharmaceutical division and the

[78] http://www.medcitylondon.com/

[79] http://www.stellar-project.be/

Innovation Center) contribute €5 million over five years. The programme is aimed at identifying new drug targets for these diseases, and validating them using laboratory and animal tests – pre-clinical testing from which possible candidate new drugs could be taken to clinical trial stages of development.

Other European collaborations since announced include a licensing agreement with a French biotech company developing antibodies which could produce new immunology drugs, venture capital investment in a Dutch biopharmaceutical company developing antibodies for cancer therapy, and working with two companies (one Dutch, one German) developing vaccines, with J&J scientists making use of technologies developed by the vaccine companies to carry out feasibility studies and further development work.

The London Innovation Center has also announced a number of regional partnerships within the UK. In June 2013, the Center established a regular presence at the Stevenage Bioscience Catalyst (SBC), the public-private open innovation partnership outlined above. The aim is for J&J to interact with those companies resident at the SBC through an on-site Partnering Office. In December 2013, the Center also established a network of Partnering Office in regional life sciences clusters in Oxford, Cambridge, Manchester, Edinburgh and Cardiff to act as extensions of the London Center and expand the ability to interact and collaborate with academics and entrepreneurs throughout the country. These regional clusters have formed around academic departments and in some cases have developed with other public investments – for example, the Edinburgh BioQuarter received funding from the Scottish Government and the Life Sciences Hub Wales in Cardiff from the Welsh Government.

Estimating the 'returns' to Innovation Centers

Successful collaborations begun at the Innovation Centers could help generate innovations developed to later (clinical trial) stages through traditional Business Development teams located both at the Innovation Centers and in other J&J companies around the world. Since the Centers have been operating only for a short time, this has not yet happened. Indeed, it is expected that it will take several years even to know whether the Centers are successfully delivering improvements in getting new ideas to a clinical proof-of-concept phase in terms of the flow of ideas and pipeline medicines being produced.

The potential for Innovation Centers to generate financial returns to the company (ignoring the potential social returns to new drugs and treatments) is thought to come from having to invest smaller amounts upfront to develop a new drug from the pre-clinical stage directly, rather than relying on more expensive acquisition of biotech or other companies who have already taken drugs to later stages of development. However there are no attempts to quantify the 'rate of return' to investments in Innovation Centers or other academic collaborations directly, reflecting the difficulties in attribution.

5 Conclusions and scope for further research

This study sets out what is known about the private and social rates of return to investments in science and innovation – 'knowledge' investments defined in a broad sense – drawing on a number of evidence sources and strands of analysis.

In the introduction, we set out three broad areas of particular interest:

- Evidence on the private and social rates of return to knowledge investments, and the ways in which social returns exceed private returns;
- Variation in the returns, in particular in terms of publicly-funded investments;
- Issues around the timing of returns, including lags between investment and returns being realised and the duration and profile of the returns.

Drawing on the evidence gathered, our conclusions on each, and recommendations for key areas for further research, are set out below.

The rates of return to knowledge investments

There is a large literature which estimates the rate of return to R&D investments, using firm-, industry- and national-level data to estimate a production function which relates economic outcomes (output or productivity) to knowledge inputs. There is clear evidence that these investments yield high private returns, of the order of 20 to 25% at the median or 30% at the mean.

Social rates of return, allowing for spillover effects between firms, industries or countries, are typically two or three times larger than this. The fact that social returns exceed private returns provides a rationale for public support of R&D investments.

However, R&D is not the only investment driving innovation. Other 'intangibles' such as design, software and firm-specific human capital represent significant amounts of investment by firms, and much less is known about the private and social returns to these wider investments.

Variation in the rates of return and the role of public investments

The best recent evidence suggests that publicly-funded R&D investments in the UK generate significant social rates of return of around 20%. This figure is based on relating private sector productivity growth to public R&D investments, similar to the way in which returns to private R&D investment are typically estimated. There is some evidence that the returns measured in this way vary according the source of funding. R&D channelled through research councils, and particularly science-based and more applied research council investments, appear to have the greatest impact on private sector productivity growth.

There are clear interdependencies between different forms of public R&D investments – for example, research council funds that go towards academic institutions. This makes it difficult to disentangle the returns by source of funds. A similar issue holds for R&D investments in capital facilities, such as science centres or datasets, and current investments in salaries and overheads. Since both work together to drive innovation, it is very hard to separate out the rates of return to these different forms of investment in a meaningful way.

A focus on how publicly-funded R&D affects the private sector is likely to underestimate the social returns to this investment. For example, public R&D investments may generate improvements in public health, national security and an intrinsic 'value of knowledge' which are not captured in a traditional knowledge spillover framework. Quantifying these benefits is much more difficult. There is also good evidence that public incentives for R&D crowd in additional private sector investments, which again would suggest larger overall returns. The evidence for crowding in is strongest for fiscal incentives and public subsidies for private sector R&D. There is less clear evidence regarding the impact of R&D conducted directly by the public sector, though the literature on this issue is somewhat thin.

There is clear evidence of an interrelationship between public and private sectors in driving innovation. Links to academia are increasingly seen as an important complement to the in-house knowledge of industry, and a significant amount of private sector output and innovation is thought to depend critically on public funding of academic research. Engagement with academia and the science base is also seen to be a key driver of where firms locate private R&D investments.

Timing and profile of returns

Empirical evidence from surveys suggests that average lag times between private sector R&D investments and commercial returns are typically quite short, around one to three years. However there is significant variation, and in many industries (including our case study sectors of life science and aerospace) typically exhibit much longer lag times, in excess of ten years.

Studies looking at the lags between publicly-funded R&D and commercial returns find much longer lags. This may well reflect a larger share of public R&D investments going towards basic research without specific commercial application in mind.

A number of studies have suggested that private R&D investments depreciate at a rate of around 20% per year, consistent with product lifecycles in the order of 10 years before obsolescence. Public investments are usually assumed to depreciate at much slower rates, if at all. This zero depreciation rate may be more appropriate for investments in basic research (which of course are not always publicly-funded) since the underlying scientific knowledge, once discovered, can reasonably be assumed to remain in place in perpetuity. Public investments in applied R&D may be subject to some deprecation, though presumably less than that for private investments if the public investment is not on a new product or process for a single firm but rather on developing innovations with broader applicability.

There is a lack of clear evidence on whether depreciation rates are constant or change over time. There is a great deal of uncertainty about the expected lifecycle of a new innovation, which can depend in part on the unpredictable arrival of disruptive technologies. Patents give some security over returns, but of course the returns will still depend on uncertain demand and there can be uncertainty over effective patent life as well if patents are granted before products are brought to market.

Potential for future research

Besides the opportunities for further econometric work highlighted in Section 3, there do appear to be a number of fruitful avenues for further analysis which could shed more light on some of the key issues of interest. These include:

- Analysis of the **wider social returns to non-R&D intangible investment**. Evidence to date has focused largely on spillover returns from public and private R&D investments to output and productivity in the private sector.
- Further **work to understand the wider 'public good' benefits of publicly-funded knowledge investments**. Most of the evidence has looked at the relationship between public R&D and private sector productivity, which is only one channel through which economic returns can be realised. Of course, the impacts of public R&D on the quality of health, education, national security and the efficiency of public service delivery are extremely difficult to measure, but further attempts to do so would be useful and add significantly to the evidence base on the returns to knowledge investments. Case studies may be one approach (e.g. building on the Wellcome Trust evidence on cardiovascular research which also drew on wider medical evidence linking the research to health benefits).
- Evidence on how **firms in non-R&D intensive industries innovate and draw on public investments to do so**. Sectors like retail, financial services, transport and utilities represent large parts of the economy, and all clearly innovate, but are much less engaged in scientific R&D and patenting than life sciences, aerospace and other traditional manufacturing industries.
- More evidence on the importance of the **interaction between different forms of knowledge investments** (e.g. capital and current spending) in generating returns would be helpful. It appears to be very difficult to

isolate the 'returns' to these different forms of investment given that they work together to drive innovation, but more evidence on these synergies and complementarities (through a combination of detailed data analysis of how R&D investments decompose across capital and current spending, and case study evidence) could help understand the issues better.

- Our case study evidence, and the emerging quantitative evidence coming from the 'microeconomic' approach to measuring returns, shed light on the **pathways linking knowledge investments to economic returns**. This would appear to be an area where more evidence would be useful, in particular understanding better the barriers which potentially inhibit returns being made at different points along the pathway, the wider influences on the returns and so on. Given the emergence of different 'micro data' approaches in different countries, and that by nature knowledge investments are highly internationally mobile, it would seem important that there is an attempt to co-ordinate across countries on efforts to collect and analyse these data so that lessons can be learned from experiences in other countries and so that future analysis can explore cross-border issues in more depth.

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Appendix A: Methodologies used to estimate rates of return

The production function approach

Methodology

Studies based on the production function usually start from a Cobb-Douglas functional form, and include labour, physical capital and a measure of research ('knowledge capital', often R&D) as inputs. The model can be applied to data at a firm-, industry- or national-level. The typical specification is:

$$Y = A \times L^{\alpha} \times C^{\beta} \times K^{\gamma} \times e^{u}$$

The variables are defined in **Table 13**.

Table 13. Explanation of the terms in the production function specification

Parameter / variable	Explanation
Y	Measure of output (should be a measure of value added unless intermediate inputs are specified in the model, in which case gross output can be used)
A	A measure that 'augments' the efficiency of labour and capital
L	A measure of the stock of labour inputs
C	A measure of the stock of physical capital inputs
K	A measure of the stock of knowledge capital
e	The exponential function
u	A random error term
α, β, γ	Elasticities of output with respect to labour, physical capital and knowledge capital respectively

The model can be augmented by additional input variables, such as intermediate inputs (materials and energy), or measures of 'external' knowledge (such as R&D

investments by other firms, industries or countries) which can be used to analyse spillover effects.[80]

There are broadly three approaches to estimating the rate of return to knowledge capital based on this starting point of the Cobb-Douglas production function:

- The first estimates a model incorporating an estimate of the size of the knowledge capital **stock** based on observed R&D flows. This approach yields estimates of the *elasticity* of output with respect to knowledge capital, which can be converted into a rate of return using information on the average size of the knowledge capital stock relative to output.
- The second estimates a model incorporating the **flow** of R&D investments relative to output. Under certain assumptions this yields a direct estimate of the *rate of return* to investment.
- The third approach recognises that R&D investments are typically only one input into **innovation** and it is this innovation which yields returns to output or productivity. This approach therefore uses measures of innovation as inputs to the production function rather whilst also modelling the impact of R&D on innovation.

We provide more detail on the methods below.

Approach 1

Start by taking logs of the production function and first-differencing, so that the model is linear in the growth rates of output[81] and the stock of inputs. First differences also remove any unobserved firm-, sector- or country-specific fixed effects (depending on the level at which the model is estimated) which may be correlated with the outcome variable.

This gives the following empirical specification which could be estimated:

$$\Delta y_{it} = \lambda_t + \alpha \Delta l_{it} + \beta \Delta c_{it} + \gamma \Delta k_{it} + \Delta u_{it}$$

[80] Note that if we simply try to include one additional variable for the knowledge capital stock of each other industry, firm or country in the model then we rapidly increase the number of parameters to be estimated. The solution is usually to use an input-output table, measures of trade intensity or some other way to 'weight' the knowledge stock of others into a single "borrowed knowledge capital" variable. This reduces the number of additional variables which need to be included in an exploration of spillover effects. Technically it may be possible construct several borrowed capital variables (e.g. into publicly funded and privately funded), given sufficient data and credible assumptions about the appropriate weights for each subset.

[81] Recalling that the first difference in logs is approximately equal to the growth rate: $\Delta k \approx \frac{\Delta K}{K}$

where *i* denotes a firm, sector or country if there is a panel aspect to the data, *t* denotes the time period, λ_t is a time period fixed-effect,[82] Δ is the first-difference of a variable and lower-case variables are logs of the upper case variables above.

Estimating a version of this equation using data on growth rates of outputs and inputs would yield an estimate of the parameter γ, the elasticity of output with respect to knowledge capital. This is *not* the same as the return to investment in knowledge capital, the key parameter of interest, though it can be derived as follows. The elasticity of output with respect to knowledge capital is defined as $\gamma = \left(\frac{\partial Y}{\partial K}\right)\frac{K}{Y}$ where $\left(\frac{\partial Y}{\partial K}\right)$ is the rate of return (how output varies with marginal changes in the knowledge capital input) of interest.[83] Given an estimate of γ from the model, and an empirical value of the ratio of the stock of knowledge capital to output $\frac{K}{Y}$ from the data, a value for the rate of return can be deduced.

For example, suppose we estimate the elasticity $\gamma = 0.1$ and from the data we take an average of the knowledge capital stock to output ratio to be 0.2. Then the rate of return to knowledge capital is 50%:

$$0.1 = \left(\frac{\partial Y}{\partial K}\right) \times 0.2 \rightarrow \left(\frac{\partial Y}{\partial K}\right) = 0.5$$

Approach 2

The second approach uses the relationship between the elasticity and the rate of return to estimate the rate of return parameter directly. Rather than including a measure of the growth rate in the knowledge capital stock on the right-hand side, it includes a measure of *R&D intensity* (flows of R&D relative to output).

To show that this specification yields a parameter estimate which can be interpreted directly as a rate of return, the following steps are necessary.

First, define $\left(\frac{\partial Y}{\partial K}\right) = \rho$ as the rate of return. Then given the definition of the elasticity parameter γ, and using the relationship $\Delta k \approx \Delta K/K$, we can write $\gamma\Delta k \approx \rho\frac{K}{Y}\frac{\Delta K}{K} = \rho\frac{\Delta K}{Y}$.

Second, note that the change in the knowledge stock ΔK is given by:

$$K_{it} - K_{it-1} = R_{it} - \delta K_{it-1}$$

[82] Included under the assumption that technical progress (A) can be modelled as a firm/country/industry effect and a time effect.

[83] Technically, we can interpret this as a rate of return under the assumption that $\frac{\partial Y}{\partial K}$ is constant, that discount rates are constant and that there is an infinite planning horizon (see Hall et al., 2009, p. 6).

That is, the knowledge stock increases each period by the amount of new investment in R&D (R) less the amount by which the existing knowledge stock depreciates in each period, δ. If there is no depreciation, the increase in the knowledge stock is just new R&D investment in each period.

Thus we have:

$$\gamma\Delta k \approx \rho\frac{R_{it}-\delta K_{it-1}}{Y}.$$

Substituting this into the previous specification gives a version of the model to be estimated as:

$$\Delta y_{it} = \lambda_t + \alpha\Delta l_{it} + \beta\Delta c_{it} + \rho\frac{(R_{it} - \delta K_{it-1})}{Y_{it}} + \Delta u_{it}$$

If we are prepared to accept that the discount rate of knowledge is approximately zero, then we can estimate the model using the ratio of investment in R&D (R) to output in each period, and interpret the parameter on that variable as the rate of return to R&D:

$$\Delta y_{it} = \lambda_t + \alpha\Delta l_{it} + \beta\Delta c_{it} + \rho\frac{R_{it}}{Y_{it}} + \Delta u_{it}$$

More properly, we should interpret it as the **gross** rate of return; estimates of the **net** rate of return require some assumption about the rate of depreciation.

In general, most studies adopt a view that aggregate knowledge stocks do not depreciate (so looking at stocks of "public" R&D, or using aggregate data on all investments at an economy or perhaps sectoral level) but that firm-specific knowledge stocks may depreciate at around 15% or so per year. The more disaggregate the level of analysis, the more important the distinction between gross and net rates of return is likely to be.[84]

Approach 3

The third approach follows the methodology by Crepon, Duget and Mairesse (1998) and is often referred to as the CDM model. This model is used by most papers that aim to estimate the relationship between innovation and productivity. The explanation below follows the explanation of Mohnen and Hall (2013).

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84 As noted in Griliches (1998), "It is quite clear that [firm-specific knowledge capital] … erodes over time, because better products and processes become available and because its own knowledge begins to lose its specificity." He goes on to argue that it may not be appropriate to assume zero depreciation of public knowledge stocks, though they are likely to depreciate more slowly than private stocks, and that it may be sensible to assume that only some fraction of the flow of public research investment contributes to the "stock" of public knowledge each year (to allow for obsolescence of old ideas, and that some investment may simply replicate existing knowledge). However he does not offer any clear guidance on what the rate of depreciation for public knowledge should be.

This model is a system of three blocks of equations. The first block models whether or not firms engage in R&D investment and, if so, how much:

$$r_1 = 1[r_1^* > 0], \text{ where } r_1^* = \boldsymbol{X_1\beta_1} + \varepsilon_1$$

$$r_2 = r_2^* = \boldsymbol{X_2\beta_2} + \varepsilon_2 \text{ if } r_1^* > 0 \text{ and zero otherwise}$$

Where $r_1$is the indicator variable which indicates whether there is R&D or not and r_2 is the intensity of the R&D. $\boldsymbol{X_1}$ and $\boldsymbol{X_2}$ are vectors of explanatory variables, and ε_1 and ε_2 are error terms.

The second block of equations models the probability that a firm 'innovates' and if so, how much (innovation is normally measured by the share of sales resulting from new products, for example). In these equations, the modelled R&D spend is included as an explanatory variable alongside other factors:

$$i_1 = 1[i_1^* > 0] \text{ where } i_1^* = \boldsymbol{W_1\gamma_1} + \eta_1$$

$$i_2 = i_2^* = \boldsymbol{W_2\eta_2} + \eta_2 \text{ if } i_1^* > 0 \text{ and zero otherwise}$$

Where i_1 is the indicator variable which indicates whether there is innovation output or not and i_2 is the intensity of innovation output. $\boldsymbol{W_1}$ and $\boldsymbol{W_2}$ are vectors of explanatory variables and include r_1^* and r_2^* or their observed equivalents. η_1 and η_2 are the error terms.

The third block of equations is the productivity equation (such as output per worker), which depends on innovation and other explanatory variables, such as physical capital intensity, which are denoted $\boldsymbol{Z}$ below.

$$\frac{Q}{L} = \boldsymbol{Z}\mu + i\phi + u$$

The impact of innovation on productivity is then given by ϕ. Hence R&D does not enter the productivity function directly, but only indirectly via innovation.

This approach typically does not estimate a 'rate of return' to R&D or other forms of innovation spending, but rather the elasticity of output with respect to innovation. Innovation and R&D spend can be modelled using continuous measures or dummy variables alone (whether or not the firm spends on R&D or innovates); in the latter case, the impact of 'being innovative' on productivity can be estimated but not a marginal elasticity.

Issues in the choice of approach

Using a capital stock or a flow of knowledge investments

The decision of whether to estimate a production function with an estimate of the capital stock or a measure of R&D intensity on the right-hand side will be driven by data availability. To the extent that we are confident to assert that the knowledge capital stock does not depreciate, then essentially the models are the same, though there is a conceptual issue that the parameter estimated (whether an elasticity or a rate of return) is treated as a constant. Hall et al. (2009, p.7) note that it may seem better to treat the rate of return $\frac{\partial Y}{\partial K}$ as a constant than the elasticity, since the elasticity depends on the level of knowledge stock and output. All else equal this would suggest estimating a model using the second approach in preference to the first.

Should productivity or output be on the left-hand side?

Some studies investigate the effect of knowledge capital investment on productivity rather than output. Productivity is normally defined by assuming:

i. constant rates of returns to scale with respect to capital and labour ($\alpha+\beta=1$); and

ii. Perfect competition

Such that the elasticities with respect to labour and capital (α and β respectively) can be interpreted as their factor shares. Then a measure of total factor productivity growth is given by:

$$\Delta TFP_{it} = \Delta y_{it} - s_{Lit}\Delta l_{it} - s_{Cit}\Delta c_{it}$$

This can be estimated given knowledge of the growth in output, inputs of physical capital and labour, and the factor shares. The model can then be re-written with productivity on the left-hand side rather than output, using either formulation above. The main effect is to remove the physical capital and labour terms from the right-hand side (since they are differenced away from output growth in defining productivity). However the interpretation of the parameters on the remaining knowledge capital variable(s) remains the same: an elasticity in the first case and a rate of return in the second case.

Whilst the assumption of perfect competition is restrictive, there are ways to relax it though it makes the interpretation of the parameter on the knowledge capital term more difficult.

Methodological challenges

A number of challenges to implementing the production function methodology have been identified in the academic literature. These include:

- **definitional** issues around the variables; and
- **econometric** issues in the implementation.

More information on these issues can be found in Hall et al. (2009), Griliches (1998) and Cameron (1998); we offer a summary below.

Definitional issues

Definition of output

When looking at firm- or sector-level data, output can be defined in various ways, including **gross output** (total value of production), **sales** (produced output less any net increase in the value of inventories) or **value added** (output less the value of purchased inputs such as energy and materials).

Value added may be a more appropriate measure of output since data on intermediate inputs are often not available. If these are excluded from a model based on gross output or sales, and they are correlated with R&D, then there will be a bias in the estimated elasticity or return.

When the dependent variable is a measure of productivity rather than output, it is usually assumed that there is perfect competition such that productivity is defined as output growth less the growth of labour and capital inputs (weighted by their factor shares). If the perfect competition assumption does not hold, then the measure of productivity will be incorrect. As noted there are more complex models which attempt to deal with this issue at the cost of making the resulting estimates more difficult to interpret.

One obvious issue is that some output may be hard to capture or measure accurately, and so the returns to knowledge capital could be understated because their impacts are not picked up in standard measures of output. For example, government investment in defence research may improve national security; this may have quantifiable benefits (if e.g. firms are more willing to locate or expand here as a result) but also benefits which are not quantifiable in terms of safety. Similar issues may be relevant to research into innovations which improve environmental quality, for example, among many others. Moreover, the benefits of some research may feed through into increases in other *inputs* (e.g. making physical capital more productive, or workers healthier so increasing the productivity of labour inputs) – this will increase output but would not be attributed to the knowledge capital investment (and the impact on measured *productivity* may be small if outputs and non-knowledge inputs both increase).[85]

Perhaps for these reasons, many empirical estimates of production functions tend to be based on firms in the manufacturing sector where outputs are more straightforward to measure. Data on the service sector in terms of R&D spend and outputs is generally harder to obtain, and likely to be subject to much more intractable problems of measurement (the value of outputs, particularly in non-marketed sectors like health and education).

Definition of knowledge capital variable

The knowledge stock variable usually has to be constructed from published measures of R&D at the firm or sector level (unless R&D intensity is used

[85] A more structural econometric model may be able to consider these second-round effects of the impact of knowledge investment on non-knowledge inputs and so consider the total 'contribution' of R&D to growth or productivity, but would be considerably more difficult to estimate convincingly.

directly in estimating the rate of return, though as noted this leaves open the question of whether the gross returns are the same as the net returns).

This throws up a number of particular issues:

- **Double counting**: R&D spending includes labour and capital costs. These need to be removed from other labour and capital input variables to prevent total inputs being double counted. Measures of value-added as output variables should also be adjusted to add in the value of R&D which is usually not included in published data (since it can be offset against profit). The empirical evidence is mixed as to the biases created by failing to account for such double counting properly.

- **Depreciation**: with firm-level data in particular, a stance has to be taken on the extent to which the stock of knowledge capital depreciates from year to year and whether this depreciation rate is constant or variable. Most standard approaches assume the stock depreciates at the same rate in each period. It is likely that in practice the depreciation rate varies across firms, sectors and over time (though in general it is assumed that, within a firm, the rate of depreciation may adjust only slowly over time).[86]

- **Setting the initial knowledge capital stock**: although a measure of the knowledge capital stock in each period can be derived from observed R&D flows under an assumption about depreciation, there is still the question of deriving the first period stock. If we are willing to assume a constant depreciation rate and growth rate within firm, this can be estimated by dividing the first R&D flow by the sum of depreciation and growth rates (which can be assumed or estimated as appropriate).

- **Deflating R&D flows to real terms**: there is an issue of the appropriate price index to use to deflate nominal R&D flows each period into real values. This could be done by constructing an R&D price index from individual prices of the components of R&D (labour, capital etc.) with appropriate weights. However there is little empirical evidence that it matters too much whether an R&D-specific price index is used or whether a general deflator is used.

Appropriate lag structure of knowledge

A clear issue for R&D knowledge stocks is that their impact on output is not necessarily immediate – knowledge built up in previous years can affect outcome

[86] Note, though, that if we are willing to assume that within-firm depreciation rates are fairly constant and that R&D stocks grow at roughly similar rates over time, then a firm-specific dummy variable will capture these reasonably well; in this case variation in the estimated knowledge capital stock based on a standard depreciation rate should still allow the model to pick up the elasticity of output with respect to knowledge capital appropriately. However the *return* to knowledge capital will still be sensitive to the assumed discount rate.

in future years (ideas take time to commercialise; basic research takes time to filter through into applications which raise output). However, if there is a relatively short time series (or the estimates are based entirely on cross-sectional data) there may be no opportunity pick up these effects in the estimation.

It is also not necessarily clear what the appropriate duration of lagged variables to include the specification would be, given the range of evidence we review (see Section 2.4.2) on lags between knowledge investments and returns.

Separability of knowledge

The formulation of the models implies that the knowledge capital stock is separable from other factors of production (in particular, this means that marginal rate of substitution between knowledge capital and another input does not depend on the quantity of any third input). This may be a poor assumption – for example, substitution between knowledge capital and labour may depend on physical capital stocks if R&D spending is more effective when capital stocks are high. This is an issue with the specification of the production function; different formulations would have different properties but may be much more difficult to estimate and demand much more detailed data than are typically available. Thus there is a trade-off between how tractable a model is to implement and how attractive its economic properties are.

Another issue relates to attempts to define different types of knowledge capital, such as public and private investments. Including them separately in the Cobb-Douglas production function model implies that they are seen as complementary, but there is an open question as to whether e.g. public funding leverages or crowds out private funding for R&D.

Quality adjustment

In general, we want to strip out the effect of general price inflation from output data and look at real levels or growth rates in any empirical specification.

However, published price series (such as GDP deflators) which are often used for this may not pick up changes in *quality*, or at least do so only with a significant delay. This means that the price series used overstate the quality-adjusted increase in price, and so understate the real value of outputs over time. This could lead to estimates of the returns to R&D being biased downwards – part of the resulting output growth is missed. This may be particularly important for product innovations which improve the range and quality of goods and services available.

One approach to dealing with this is to use **panel data** and to include time dummies which could pick up variation in quality over time. With firm-level data these dummies could be both time- and sector-specific to allow for differential quality changes across sectors.

Quality may also be an important issue for input data. Again, the real value of inputs is needed, and so published price series may overstate true increases in price. In addition, it may not simply be appropriate to include an overall labour or physical capital input in the specification, but to allow for inputs of different quality (for example, skilled and unskilled labour; new and old vintage physical capital). Across firms or sectors, it may be that those who employ large amounts of skilled labour are also more R&D intensive; failing to control separately for labour quality could therefore overstate the impact of R&D on output through an omitted variable channel.

Econometric issues

Measurement error

Even if appropriate definitions of the output and input variables can be found, there is a question as to how accurately they are measured. If variables are measured with error, in general the estimates from an econometric model will be biased (if the error is random, then the bias will be towards finding zero returns). In models estimated using first differences, measurement error will be further exacerbated.

Along with other problems related to endogeneity (see below), this may be a particular reason to consider instrumenting measures of R&D in econometric models.

Omitted variable bias

A production function model may also need to control for other covariates which affect output (or productivity, depending on the specification of the dependent variable). If omitted variables influencing output are correlated with the (included) R&D stock, flow or growth rate then their effect may be attributed to the R&D variable leading to biased estimates. The direction of the bias will then depend on the direction of the correlation between the omitted variable and the R&D measure.

There are a number of potential variables that could be included in an econometric model, including:

- **Measures of cyclical variation**, which could include estimates of the output gap (or capacity utilisation), or time-specific dummies.
- **In cross-sectional studies, firm-specific measures of the extent to which returns to R&D can be appropriated, or the extent to which firms are at or behind global technology frontiers**. If there are no measures of such variables they may be captured by firm- or sector-specific dummy variables.
- **Intermediate inputs** (as noted above if gross output is used as the dependent variable).

- **Labour or capital quality** (as noted above in the discussion of quality variation in input variables).

The extent to which time- or firm-/sector-specific dummies can pick up various other influences on output will of course depend on the level of analysis. It will not be possible to pick up any effect of knowledge capital on output if dummy variables which are completely collinear with the variation in knowledge are included (e.g. we could not control for period-specific fixed effects if there is only time variation in knowledge; in that case we may have to control for e.g. a time trend or a dummy variable indicating periods of recession).

Endogeneity through simultaneous determination of outputs and inputs

A process of supply and demand in goods and factor markets will jointly determine outputs and inputs in each period. Levels of R&D investment will in themselves be determined in part by output in previous periods.

Empirical models based on a model linking output growth to input growth are therefore susceptible to an endogeneity bias in the independent variables. In the context of the models set out above, the k_{it} variable is correlated with the error term u_{it}. The empirical evidence on the direction of this bias is somewhat mixed.

One strategy is to use instruments (such as appropriate lags of labour or physical capital inputs, which are correlated with current inputs but not directly with current output), though there is some evidence that instrumenting in differenced equations is not particularly successful. For the knowledge capital variable, lagged values are poor instruments since they may well affect current output directly (see above), though other possible instruments include e.g. the presence and magnitude of fiscal or other policy incentives for R&D.[87]

Using a fixed-effects model with panel data (e.g. where firm- or country-specific dummy variables are included) may also help overcome endogeneity problems under particular assumptions about the form of the error term (notably, that there is a permanent component which affects input choices and a time-varying component which does not).

Multicollinearity

Time-series measures of outputs and inputs often move together in similar ways. This can make disentangling the effects of individual inputs in a credible way very challenging without sufficient variation in the data, or making additional prior assumptions.[88] Using cross-sectional or panel data is therefore the most common

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[87] Griliches (1998) notes that factor prices can be used as instruments, but the problem is that the 'price' of R&D is usually poorly defined.

[88] For example, if input variables move together then as described above we can remove labour and physical capital inputs from the specification by using TFP as the dependent variable and regressing it on knowledge capital (plus other covariates as appropriate). This requires assumptions about

approach to estimating production functions rather than pure time-series, since it allows for variation across units of observation (firms, industries or countries) as well as across time to identify the model.

Sample selection

There are a number of possible issues related to the construction of the sample for estimation (these relate in particular to firm- or industry-level studies):

- **Selection bias/survivor bias**: the data may not record firms who do not engage in R&D. If returns are higher for those who engage in R&D then there will be a selection bias in the estimate. Similarly, data may exclude firms who go out of business or firms who merge (for whom returns may be higher or lower). In principle one could use selection models or try to estimate a stock of knowledge capital even for firms who do not engage in R&D. Empirical evidence on the importance of this is mixed.

- **Outliers**: some firms may engage in very high levels of R&D or have particularly high or low output in given periods; there is an econometric issue of whether or not to include outlier values in the estimation. Some studies suggest the estimated elasticities or returns are somewhat sensitive to how outliers are dealt with.

Examples of the microeconomic approach

STAR METRICS

The STAR METRICS project aims to use widely-collected administrative data to estimate the direct and indirect impact of federally-funded research institutions such as universities. Lane and Schwarz (2012) give an account of the data sources, though broadly the data are made up of detailed records of the research contracts held by institutions and the staff supported by the contracts. The individual scientist is the main unit of analysis in the generated dataset. There are two parts (levels) to the project.

Level I aims to develop an automated data infrastructure to analyse:

- What research and development is being done with federal funding?
- Who is doing the R&D?
- What is the effect on employment?

The aim is to make the data collection process as automatic as possible. What R&D is being done and by whom is based on language processing techniques being applied to grant award documents to elicit the characteristics of the

competition and returns to scale in physical capital and labour inputs; these assumptions impose prior restrictions on the output elasticity of those inputs.

research including the subject and type of research (e.g. basic versus applied). Data held by human resources departments in research institutions is used to assess who is carrying out research (based on which grants are used to actually remunerate researchers, not just who the lead investigators are) and what sub-contracting arrangements are in place.

The employment effects consist of direct research jobs supported by federal grants (whether directly or through sub-contracting) and indirect impacts such as wider non-research employment in research institutions (like administrative roles) and the supply chain for those institutions (such as building new facilities). These indirect effects are estimated by matching identifiers between collaborating institutions and vendors, and to industry census data.

Initially piloted at 6 research institutions, Level I now covers over 100 organisations, making up some 45% of National Science Foundation and National Institute of Health funding.

Level II of the project aims to develop wider outcome measures from the funding, including research outputs, wider (induced) employment outcomes, social outcomes, and economic growth. This phase of the work could in time lead to new ways to estimate the rates of return to initial investments through a detailed way to trace their impact into outcomes based on administrative data.

The aim of Level II is to go beyond the traditional emphasis on bibliometric methods, analysing also other channels for the transmission of knowledge, such as students' labour market outcomes. Some smaller-scale studies aiming to link STAR METRICS data to wider outcome data sources are underway to investigate what might be possible in Level II.

Industry and Academic Engagement Projects

Researchers at Imperial College, London are compiling datasets on the research staff at the College which, ultimately, could help tie research investment inputs to academic and wider economic outputs.

The first part of the work is the Industry Engagement Project, which is using administrative data from the College to compile information at the individual academic level. This includes information on research inputs and teaching activities – details of grants and contracts awarded, courses taught and PhD students supervised. It also contains data on research outputs, including academic and non-academic publications, patents, licences and income generated spin-off companies, media impact, links with industry (e.g. board membership) and consultancy work. Data over roughly ten years may be available for the population of around 10,000 academics employed by the College over that period. The data includes demographic characteristics of the individual academic. The intention is to focus on the *breadth* of the data collected rather than the *depth*, and so is aiming to compile as wide a set of indicators of research outputs and wider engagement as possible.

The database compiled will be linked with information from a survey of current Imperial academics which looks more at attitudinal issues. This survey forms the Academic Engagement Project, which focuses on understanding the underlying behaviours and perceptions which influence some of the observed outcomes from the Industry Engagement Project. This includes perceptions of the benefits of academic engagement with business, perceived issues around career implications and relationship to family life and academics' views on the role of academia in business.

Together, the database should allow considerable insights into a research "production process" leading to academic and wider outcomes at a fine level of granularity. This will include evidence on the relationship between industry engagement and research outputs, how different types of engagement link into wider engagement and spin-off activities, the barriers to engagement and how this relates to various output measures, the links between different funding profiles and research outcomes, and how research outcomes relate to the structure and composition of research teams. In principle, given the detailed information on the type of research investments and the outcomes, it may be possible to derive some estimates of the returns to different forms of investment, at least insofar as monetary values can be assigned to the different outputs, and the contribution of each input to the measured outcomes can be identified.

Appendix B: Evidence summaries

Table 14. Variation in the private sector returns to publicly- and privately-funded R&D

Authors	Country	Period	Unit of analysis	Return to publicly-funded R&D	Return to privately-funded R&D
Leonard (1971)	US	1957-1963	Industry	Insignificant (positive excluding defence)	
Terleckyj (1980)	US	1948-1966	Industry	Insignificant	20-27%
Link (1982)	US	1977	Firm	Negative	
Griliches and Lichtenberg (1984)	US	1959-1976	Firm	Insignificant	33.9%
Griliches (1986)	US	1957-1977	Firm	Positive	Positive, exceeds public
Lichtenberg and Siegel (1991)	US	1972-1981	Firm	Insignificant	13.2%
Nadiri and Mamuneas (1994)	US	1970-1986	Industry	6.8% (public infra-structure)	9.6%
Lichtenberg (1993)	Various	1960-1985	Country	Insignificant	6.6%
Park (1995)	Various OECD	1970-1987	Country	Insignificant	44% (49% i/c cross-country spillovers)
Guellec and De La Potterie (2003)	Various OECD	1980-1998	Country	Positive (universities)	
Di Cagno et al. (2013)	Various EU	1994-2005	Country	Insignificant	Significant positive elasticities
Haskel and Wallis (2010, 2013)	UK	1986-2007	Country	Positive (research councils); Insignificant (others)	NA
Haskel et al. (2014)	UK	1992-2007	Industry	Around 20% (total research councils + higher education + government)	Private (industry-level) returns around 10%

Source: Frontier Economics

Table 15. Case study evidence on the returns to publicly-funded research

Report	Investment	Type of analysis	Findings
Wellcome Trust (2009)	Research into cardiovascular disease in the UK between 1975 and 1992.	Health gains estimated using estimates of proportion attributable to UK research of the Quality-Adjusted Life Years (QALYs) gained through CVD research, net of the health service costs to generate them, and allowing for a lag between research and health gains of 17 years. GDP gains estimated using evidence on additional private R&D leveraged by the public R&D and estimates of social rates of return to R&D spending.	Central estimate of total return of 39% (9% from health gains and 30% GDP gains). Estimated range of 6 to 14% for health gains and 24 to 36% for GDP gains.
STFC (2010)	Second generation multi user X-ray synchrotron radiation facility	Reports on the direct spending of the facility, and uses multipliers generated by the ONS to estimate indirect and induced impacts over the facility's lifetime. Specifically, the study used the ONS national multipliers for R&D spending: 0.44 for induced impact and 0.23 for indirect impact.	£1 of spending on the facility generated £0.67 in additional economic activity through indirect and induced impacts. Construction and operation of the facility generated £594m spending, £534 of which in the local area (North West England). The indirect and induced impact was then £398m.
Battelle (2011)	The Human Genome Project, an international public project led by the U.S.A., aimed at identifying all the genes in human DNA, and determining the sequences of the chemical base pairs that make up human DNA. It required $5.6bn[89] in total U.S. funding.	Uses the IMPLAN input-output model. The direct impacts used as input are threefold: the direct federal funding of the HGP; the impacts of follow-on investments by the U.S. National Institutes of Health, and the U.S. Department of Energy; genomics-related R&D spending in the pharmaceutical industry and production in "genomics-enabled" industry.	The total multiplier for HGP federal funding between 1988 and 2003, taking into account both indirect and induced impacts, is 2.98 – $1 spending determined additional $ 1.98 in economic output. The direct impact on U.S. output of the genomics-enabled industry over the 1993-2010 period is $21.4bn. The impact multiplier is 3.01 - $1 spending in the genomics industry determined additional $2.01 in economic output.

Source: Frontier Economics

[89] All figures from Battelle (2011) are in 2010 U.S. dollars.

Table 16. Literature on engagement between academics and business

Authors	Location	Findings	Data
D'Este and Patel (2007)	UK	On average, around 50% of the academics surveyed have engaged in consultancy or contract research and in joint research. The proportion is highest for Engineering and Metallurgy & Materials. Individual characteristics are more influent than institution characteristics in predicting interaction. There is a weak negative relation between institution quality and engagement	Survey data on a sample of 4,337 UK researchers, drawn from the population of grant holders from the Engineering and Physical Sciences Research Council (EPSRC) between 1999 and 2003
D'Este and Perkmann (2011)	UK	Patenting and academic entrepreneurship are solely motivated by the commercial exploitation of knowledge, while engagement is mainly motivated by research-related motives, including access to in-kind resources such as equipment or research expertise	Survey of EPSRC grant holders (see above)
Abreu et al. (2009)	UK	Motivations for engaging in collaboration with external organisations include, besides looking for a source of personal income, other objectives such as gaining insights in the area of research, testing the practical application of research, securing access to specialist equipment, materials, or data	The Centre for Business Research survey of 22,170 individuals in the UK academic community active in research or teaching in 2008/09
Bekkers and Boidas Freitas (2008)	Netherlands	Patents and licenses are very important in material science and chemical engineering, not in computer science, where collaborative and contract research is more relevant, as is also the case for medical science	Survey data on 575 Dutch academic researchers, and 454 industry researchers, collected in 2006
Hughes et al. (2013)	UK	Academics in highly rated RAE assessment units are more likely to interact with industry through a variety of channels. However, RAE ratings do not seem to be correlated to the extent to which research is applied in a non-academic context or is perceived to be of commercial relevance. Holding RAE assessment constant, grant holders are more likely to produce research applied commercially and to be involved in commercialisation of their knowledge	CBR Survey of UK academics (see above)

Source: Frontier Economics

Appendix C: Robustness checks for econometric analysis

Table 17. Social returns by public R&D type, using intangible-adjusted TFP measure

Regression	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep. variable	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	
Constant	0.0347** (0.0131)	-0.0335 (0.0533)	-0.0259** (0.0108)	0.00419 (0.0278)	0.0246** (0.00953)	0.0561*** (0.0141)	0.0212*** (0.00705)	
Public R&D expenditure	-2.207* (1.188)							
EU contribution		76.11** (33.20)	66.17*** (18.66)					
Research councils		-2.105 (16.05)		2.245 (12.03)				
Civil expenditure		5.648 (12.52)			-7.055 (4.448)			
Higher education		5.852 (29.69)				-21.35*** (7.007)		
Defence		-4.165 (2.551)					-2.759 (1.665)	
Research councils (to 2004)								59.35** (22.96)
Research councils (to 2005)								53.98** (20.63)
Research councils (to 2006)								31.40* (17.33)
Research councils (to 2007)								16.23 (13.04)
Research councils (to 2008)								2.245 (12.03)
Observations	21	21	21	21	21	21	21	
R-squared	0.170	0.493	0.383	0.003	0.153	0.190	0.152	

Source: Frontier Economics

Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the first lags of R&D.

Table 18. Social returns by public R&D type including additional control variables

Regression	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	ΔlnTFP	
Constant	0.00586 (0.0154)	-0.0785 (0.0504)	0.00456 (0.0151)	-0.0186 (0.0325)	0.00618 (0.0152)	0.00763 (0.0200)	-0.0158 (0.0284)	
Public R&D expenditure	-1.416 (2.656)							
EU contribution		54.92 (32.76)	18.32 (20.08)					
Research councils		-0.0616 (18.01)		7.119 (9.066)				
Civil expenditure		-12.53 (10.64)			-3.093 (4.861)			
Higher education		36.71* (19.98)				0.414 (7.313)		
Defence		2.123 (5.056)					-3.435 (3.566)	
Private R&D expenditure	-5.355* (3.014)	-2.378 (3.563)	-5.625 (3.196)	-4.627 (3.406)	-5.534* (3.021)	-5.743 (3.483)	-4.150 (3.407)	
US/UK Prod. Frontier	-0.0839 (0.0977)	0.0163 (0.128)	-0.0377 (0.113)	-0.0918 (0.0920)	-0.0778 (0.0965)	-0.0975 (0.0953)	-0.0792 (0.0962)	
Foreign GovERD	0.0309* (0.0161)	0.00774 (0.0153)	0.0234 (0.0149)	0.0264 (0.0152)	0.0289* (0.0150)	0.0287* (0.0158)	0.0306* (0.0146)	
Δ internet penetration	0.00112 (0.00066)	0.000667 (0.00070)	0.00108 (0.00068)	0.00121* (0.00068)	0.00116 (0.00068)	0.00118 (0.00072)	0.00103 (0.00065)	
Research councils (to 2004)								46.08* (21.91)
Research councils (to 2005)								44.97* (21.40)
Research councils (to 2006)								41.61* (19.41)
Research councils (to 2007)								16.91 (12.39)
Research councils (to 2008)								7.119 (9.066)
Observations	20	20	20	20	20	20	20	
R-squared	0.303	0.456	0.326	0.309	0.306	0.289	0.325	

Source: Frontier Economics. Notes: Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level. All R&D variables included are the second lags of R&D. The final column shows the coefficient on the research council variable as the sample period changes; these come from separate regressions which also control for the additional control variables outlined.

Table 19. Social returns to research council R&D, by sample period and smoothing method for TFP growth

Regression	(1)	(2)	(3)	(4)	(5)
Smoothing approach	**3 year (baseline)**	**5 year**	**7 year**	**No smoothing**	**Lead and lag smooth**
Research councils (to 2004)	39.47* (19.45)	17.92** (6.389)	8.402 (5.924)	11.37 (22.38)	46.78** (20.20)
Research councils (to 2005)	38.98* (18.92)	17.44** (6.224)	8.162 (5.896)	9.356 (21.46)	43.12** (19.09)
Research councils (to 2006)	36.75* (17.48)	16.47** (5.940)	7.675 (5.568)	8.685 (20.07)	25.93* (13.85)
Research councils (to 2007)	22.25* (11.98)	11.86** (4.349)	5.247 (3.192)	14.88 (11.51)	15.97 (9.594)
Research councils (to 2008)	10.71 (9.472)	5.536 (4.979)	1.850 (2.988)	-12.60 (21.66)	-7.112 (16.10)

Source: Frontier Economics. Notes: Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** at the 5% significance level and * at the 10% significance level. All R&D variables included are the second lags of R&D. “No smoothing” uses the raw year-on-year TFP growth rate as the dependent variable. “Lag and lead” smoothing follows Haskel and Wallis (2010, 2013), taking a weighted average of TFP growth in year *t*, year *t-1* and year *t+1*, weighted 50%, 25% and 25% respectively. All other smoothed averages use simple weighted averages of lagged TFP growth over the number of years specified. In the final column we report coefficient estimates from the one-year lag of research council spending relative to value added; all other columns report the two-year lag.

Table 20. Social returns to research council R&D by sample period and choice of lag structure

Regression	(1)	(2)	(3)
Lag of R&D to value-added	One year	Two years (baseline)	Three years
Research councils (to 2004)	30.84** (14.17)	39.47* (19.45)	26.23 (16.53)
Research councils (to 2005)	29.26** (13.23)	38.98* (18.92)	26.22 (16.35)
Research councils (to 2006)	17.29 (9.968)	36.75* (17.48)	26.04 (15.89)
Research councils (to 2007)	13.43* (7.053)	22.25* (11.98)	25.25 (14.52)
Research councils (to 2008)	6.206 (6.691)	10.71 (9.472)	8.514 (12.03)

Source: Frontier Economics

Robust standard errors are reported in parentheses. *** indicates a result significant at the 1% significance level, ** indicates a result significant at the 5% significance level and * indicates a result significant at the 10% significance level.

Appendix D: Outline topic guide

This version of the topic guide was shared with companies who agreed to participate in the case studies, to give them a brief overview of the aims of the wider project, the objectives of the case studies and the broad issues which would be covered. The interviews themselves were conducted with a more detailed topic guide, which contained ideas for follow-on questions and prompts.

Introduction

This case study is taking place as part of a wider project commissioned by BIS which aims to provide up-to-date evidence on the private and social rates of return to investment in science and innovation, how these returns vary depending on the type of investment and over time, the role of public investments, and the external factors which influence the returns.

The case studies will involve an initial interview with one or more people in the company who have a broad overview of the research and innovation process in that firm. The initial interview will cover issues at a fairly high level. We would then like to identify a couple of examples of recent innovations (products, processes, organisational) within the firm, and interview people involved directly with that innovation (relevant project managers or researchers) to drill down into some issues in more depth. This may also include people outside the company – for example, academics, facilities managers, investors and so on.

The initial interview should last about an hour. Follow-up interviews would vary in length but none should be longer than an hour. We may also need to follow up with people by phone or email to fill in some details that we weren't able to cover off in the interviews.

All interviews would (with permission) be audio recorded, but the recording would not be available outside the Frontier Economics project team. Individuals and companies involved in the case studies can remain anonymous if preferred.

Topics covered in the initial interview

The broad purpose of the initial interview is to understand how the firm:

- approaches innovation and research; and
- interacts with the publicly funded science-base, that is, academic and other state supported research institutions, in the innovation process.

This will involve us asking questions about the following issues – this is not an exhaustive list but an indication of the sorts of issues we hope to cover.

Innovation

- How the company thinks about innovation and what sorts of investments are considered to be contributors to innovation.
- What the main drivers of innovation are thought to be within the company.
- A broad overview of the innovation process within the company, and how long that process tends to take to come to fruition.
- Whether the innovation process and investments in innovation have changed recently.
- The outcomes of innovation and the expected shelf life of innovation.
- How innovation is valued and the perceived risks around innovation.
- The role of public sector in the innovation process, including funding.

Research

- The sorts of research activity the company engages in internally and collaboratively to drive innovation.
- The internal research process within the company and how decisions about research are made. Factors which influence these decisions and processes.
- How the company makes use of external research produced by the public sector or other companies, including general relationship with academia.
- How (else) the company interacts with public funding in the research process, e.g. use of facilities, knowledge transfer programs, grants.
- The importance of different publicly-funded investments in driving the company's own research and innovation: the extent to which the public funding is critical or marginal in the process, the extent to which it substitutes for or complements what the company does itself.
- Whether engagement with public funding has changed recently.
- Perceived barriers to engagement with publicly funded investments as part of the research and innovation process, or how barriers have been successfully removed.

Issues to cover in follow-up interviews

Essentially we are trying to understand in a bit more detail some of the linkages between public investments in research and innovation and how they contributed (if at all) to some recent examples of innovation within the company.

The key questions these examples cases will address are:

- What was the origin of this innovation and how was it brought to fruition?
- What factors affected the decision to invest in the innovation?
- What sorts of investments were needed for the specific innovation?
- The costs of developing the innovation and the returns/impact – how are these assessed and measured?
- What was the role of public funding in this innovation, if any? Was this public investment critical or not to the innovation being realised?
    - Academic research
    - Publicly funded facilities
    - Direct public investment in the firm, tax incentives, loans
    - Staffing, skills and training
- What (additional) investment did the company make to bring about the innovation?
- How old was the publicly funded research that was relevant?
- What made any collaboration successful or unsuccessful – could things have been done differently to improve things?
- How long is the company likely to benefit from the innovation? Will this increase or erode over time?
- How is the value of the innovation measured/judged and can the value of any public sector contribution be identified separately?

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