ECONOMIC IMPACT OF THE NATIONAL MEASUREMENT SYSTEM

Prepared for the Measurement Board by

Dr Ray Lambert

Senior Economist

Department for Business, Innovation and Skills

LONDON, UK.

METROLOGY EVIDENCE PAPER

Introduction and Summary

This report is a summary compilation of recent evidence on the National Measurement System (NMS), its importance in the research base, and its contribution to business innovation and economic performance. It covers analysis of the underlying economic logic for public support of metrology in the UK, empirical evidence on the role of measurement science in the overall science system and its impact on national economic outcomes. The impacts are measured and assessed using both statistical sources and case studies. The report examines the various paths through which metrological science and measurement knowledge and practice disseminate through and have impacts on economic activity and performance. The report has the following structure:

Chapter 1 establishes the case in principle for public funding of metrology and is the executive summary of a study of the underlying rationales for public spending on the NMS, by Peter Swann of Innovative Economics. From the range of arguments adduced there, two can be drawn out-here.

Metrology as a public good:

- The fixed costs of each metrology research project are relatively high but the marginal costs of spreading the acquired knowledge to users is small, and the applicability of the results is very generic.
- Privately-funded metrology projects are liable to have rich externalities for other potential users

Measurement as General Purpose Technology:

- Measurement is one of the infra-technologies, which underpin current and future further innovation. Other infra-technologies include information and communications technologies

(ICTs), which share with measurement the property of combining immediately usable knowledge while providing platforms for further research and applications development.
- Measurement can also be considered a general purpose technology: that is, very widely applied across private and public economic activity and with scope for continuous improvement. Indeed developments in other infra or general purpose technologies such as ICTs and the application of global positioning technology are dependent on continuous improvements in measurement science and the wide dissemination of the resulting knowledge and best practices. Advances in measurement science and techniques are also essential when major new challenges such as global warming or the effects of volcanic eruptions on weather and atmospheric conditions need to be addressed by private business and public policy. Through the rest of this report, the measurement system is considered under the more encompassing description of General Purpose Technology (GPT).

These insights underpin the empirical analysis that follows in subsequent Chapters.

Chapter 2 covers the route to impact through business innovation and is a summary of a study by Paul Temple, University of Surrey, of the contribution of measurement knowledge to business innovation. This novel research finds a positive relationship between the extent of measurement knowledge available to business sectors and the types and degree of innovation carried out by firms in those sectors. A striking result is that measurement knowledge is more strongly associated with novel than with 'catch-up' innovation; that is, it underpins leading-edge product and process innovation.

Chapter 3 deals with measurement science as part of the public science base and private sector research and development. It is the summary version of a paper by Michael King, University of Manchester, which uses detailed data on publications by NMI scientists to examine the interactions between measurement science and university research, through joint projects and publications as well as citations by publications in other fields of science of metrology publications. The conclusion is that metrology is deeply embedded in the national research effort with a growing number of publications jointly with University researchers, while metrology papers are heavily cited in other scientific publications.

Chapter 4 examines the general purpose technology aspect of metrology through the impact on national economic performance outside of the route through business innovation. It is derived from a paper on types of innovation and their relation to productivity and growth by Marion Frenz of Birkbeck College and Ray Lambert. The measurement knowledge indicators developed by Paul Temple are found to have a positive and statistically significant contribution to productivity and growth that is complementary to that of product and process innovation, reflecting the nature of measurement as a general purpose technology, pervasive in production and distribution as well as in innovation. The implied elasticities of performance on increases in the stock of measurement knowledge, especially for more advanced user groups are high.

Case studies of the use of specific measurement results in business or public policy applications are included at appropriate points in the text. These have been prepared by Sagentia Ltd on the basis of discussion with the NMIs and the firms and organizations concerned. The 'bottom line' impacts of these applications are found to be several times the public investment required to develop and disseminate the measurement resource concerned.

In sum, the accumulated evidence of a variety of types confirms the conclusion reached over 10 years ago in a previous review of the NMS: that investment in this national infrastructure resource generates an impressively high level of economic benefit via several complementary routes. Note that this evidence is exclusive of the role of measurement in the development and delivery of public services, such as healthcare and forensics, which are also known to be highly significant.

Chapter 1: Rationale

(Peter Swann, Innovative Economics Limited and Nottingham University Business School, UK)

Executive Summary

This report gives an overview of the economics of metrology and measurement, and government policy towards these activities. It makes a distinction between metrology (the science of measurement), the construction of measurement tools, and everyday measurement activities.

The report addresses four main questions:

- Why are metrology and measurement economically important?
- Do we need to have a policy for metrology and measurement, and if so, why?
- Where do we have to intervene, and where can we trust the market?
- How do we establish priorities for policy?

The report shows that metrology and measurement are important for their contribution to productivity growth, and that this can come through the use of interchangeable parts, the use of measurement in process control, and the role of measurement in improving decision-making and in reducing the regulatory burden.

Metrology and measurement are important in supporting innovation, whether by improving the effectiveness of the R&D process or by making it easier for the innovative producer to market innovative new products to sceptical customers.

Metrology and measurement are also important in helping to reduce transaction costs and in limiting market failure.

Moreover, the report stresses that the beneficiaries of improved measurement are not just companies but include consumers, health care professionals, environmentalists, as well as teachers and their students.

The report summarises the leading arguments for having a policy towards metrology and measurement. Metrology projects have two characteristics in particular that give them a special public good character. First, the fixed costs of each project are relatively high but the marginal costs of spreading the acquired knowledge to users is small, and moreover the applicability of the results is very generic. Second, privately-funded metrology projects are liable to have rich externalities for other potential users.

The main case for policy rests on these characteristics, but there are three other reasons why it may be important to have a policy towards measurement and metrology: first, the importance of 'network effects' to users of the measurement infrastructure; second, the need to ensure that metrology remains open to all users and is not monopolised; and third, when there is a special need for impartiality and integrity in measurements.

The report argues that intervention is most important when the ratio of fixed costs to marginal costs, as described above, is high or where externalities are important. It is argued that these conditions are most relevant to metrology (research? development?) projects. But intervention may also be required when network effects, openness or impartiality are of special importance. By contrast, intervention is not required when fixed costs and externalities are low – and that is the case with many day-to-day measurement activities.

The report describes two approaches to defining priorities for public funding. One ranks projects according to the externalities they create, and also the ratio of consumer to producer benefits. This approach has its attractions but is difficult and costly to apply in practice. Another approach suggests some seven criteria (based on the above arguments) which can be used to assess which

projects are greatest priorities for public funding. The report reminds us that a final criterion should always be considered in setting priorities: will further advances in measurement encounter diminishing returns?

Policy Makers' Summary

1. Introduction

The main report gives an overview of the economics of metrology and measurement, and government policy towards these activities. This Summary for Policy Makers attempts to provide concise answers to four main questions which are likely to be of greatest concern to policy makers:

- Why are metrology and measurement economically important?
- Do we need to have a policy for metrology and measurement, and if so, why?
- Where do we have to intervene? Where can we trust the market to allocate the required resources to metrology and measurement?
- How do we establish priorities for policy?

In addition, we shall at the end make a few observations on a final question, though a full answer to this lies well beyond the scope of the present report:

- How important is it for government to provide resources to support metrology and measurement compared to other spending priorities?

But first, it is helpful to have a brief discussion of what activities are encompassed by the terms metrology and measurement.

2. Definitions

The title of the main report refers to measurement and metrology. We reserve the word metrology for a subset of measurement activity: "metrology is the science of measurement". In particular, the report is concerned with three areas of activity:

1. Metrology, including basic research on measurement, refining state-of-the-art measurement methods, and the discovery of novel reference materials.
2. Tools, encompassing the construction of measurement tools and infrastructure to carry out measurement, including method evaluation and development, proficiency schemes and the production and certification of reference materials.
3. Applications, encompassing the day-to-day use of tools and techniques for real-world measurement.

The report shows that the economic and policy issues around metrology are rather different from the economic and policy issues around the other two areas.

Research is pursued mainly in the public sector - in universities and government-funded research laboratories. By contrast, the development of measurement tools and infrastructure may be located in both the public and private sectors. And the day-to-day use of tools and techniques is widely dispersed across public and private sectors - in labs, companies, many parts of the public sector, and by the individual customer at home.

From an economic perspective, the three categories are rather different. Research on metrology has very large fixed costs, but is of quite general applicability and its results can be disseminated at relatively low marginal cost. Developing new tools also has significant fixed costs, but the marginal production cost per tool is not trivial. The use of measurement for day-to-day purposes usually has the lowest degree of fixed costs, but such measurement activities are often highly specific to the user.

The policy case for public support also varies across the three categories. The case for the public support of metrology research is the strongest and is similar to the traditional argument for supporting basic research. But in general, there is much less need for public support of the development of measurement tools and little or no need for public support of the day-to-day applications of measurement. The latter can usually be left to the market – with one notable exception, noted in the next paragraph.

In a market economy, measurement activities are located in two different places. First, each organisation in a market economy makes measurements for its own internal purposes and to ensure that it meets regulations. Like any other investment, it is usually the organisation's own business to ensure that it spends the appropriate amounts on the relevant measurement activities. Second, measurement is part of the exchange between organisations in a market economy. Here, there may be a need for policy intervention because of a possible mismatch between the measurements that the supplier is willing to supply, and the measurements that the customer would like. We return to this point in Section 4 of this summary.

3. Why is measurement economically important?

Much of the main report discusses the analysis of the economic effects of measurement. In brief, there are four main areas in which measurement has important economic effects, even in the short term.

(a) **The use of measurement can increase the productivity of organisations.** This was first seen in the eighteenth and nineteenth centuries with the development of interchangeable parts; this became an important aspect of the so-called American System of manufacturing. The use of precise measurement revolutionised interchangeable manufacture because it enabled an effective and efficient division of labour. Later, measurement became one of the integral parts of process control and continues to be integral to advanced manufacturing. The more precise is the measurement and the more rapid is the feedback from measurement to control, the greater are the effects on efficiency, quality and productivity.

There are some other indirect channels by which measurement can enhance productivity. Improved measurement can support better decision-making in organisations, with fewer errors in decision-making, less waste and therefore greater productivity. Moreover, improved measurement can help to reduce the burden of regulation.

(b) **Measurement supports innovation.** It can do this in a variety of ways. The main report describes the example of how the Wright brothers used measurement as part of their research into the aerodynamics of aircraft wings and, building on that, as part of their development effort to build the first viable aeroplane. The main report also cites more modern examples of how publicly funded metrology activities have helped to support innovation by Rolls Royce and Boeing. These examples all illustrate a virtuous circle in which measurement supports R&D and innovation.

Measurement is also important to the innovator as it offers an objective way to demonstrate to customers that an innovative product is indeed superior to the competition. In the absence of any such measurements, the sceptical customer may be unconvinced, but if the superior product characteristics can be measured in an objective (and independently verifiable) way, then this supports the marketing effort of the innovative producer. In this way, measurement can play an important role in avoiding market failure for innovative new products.

Another related example is the use of measurement to demonstrate the purity and quality of premium products. And the intimate relationship between measurement and innovation is illustrated in the main report by a case study of a company which needed to develop its own measurement instruments in order to demonstrate the superiority of its products, and this was the first step in the diversification of the company from optical manufacture into instrumentation for advanced metrology.

(c) **Improvements in measurement can help to reduce the transaction costs between suppliers and customers in a market economy.** One of the most common sources of market failure is asymmetric information between buyers and sellers, where the buyer cannot distinguish good products from bad and therefore does not buy. Often this arises because measurement is difficult or expensive. As measurement improves and becomes cheaper, then buyers can measure any product characteristics they wish to, and that eliminates the asymmetric information and reduces the transaction costs. Indeed, many producers use measurements of product characteristics to advertise their products. Moreover, the danger of asymmetric information is not just that there will be market failure; another possibility is that buyers will underestimate the risk of purchasing a bad product and will buy when they should not do so.

(d) **Measurement can help a broader group of beneficiaries than those considered so far.** For example, many consumers are interested in careful measurement of product characteristics to ensure quality, safety, purity, dosage accuracy and so on. The main report cites many examples including food composition data, the alcohol content of drinks, the sun protection factors of sun-block, the speed of a car and the temperature of its cooling system, the performance characteristics of hi-fi, and the accurate and early detection of carbon monoxide in the home.

In the health service, clinicians depend on the precise measurement of doses, which is essential for efficacy and safety in medicines and for the diagnosis of medical conditions. They also make extensive use of measurement instruments to check patient health (blood pressure, blood tests, and so on). Such measurements are not only important in managing the health care of individual patients, but are also important in the context of epidemics.

Those concerned with the environment depend on measurement for accurate information about meteorological conditions (wind, rainfall, sunshine, temperature, etc.), pollution and emissions (including carbon dioxide emissions), geo-seismic measures, measures of the ozone layer, measures of the condition of the polar caps, and so on. And measurement has at least three important roles in education and training: as part of the curriculum, as an essential input to the research process, and in assessing student aptitude and performance.

These four categories cover the main economic effects of measurement visible in the short term. Economic historians have also identified some longer term implications of measurement. One ambitious thesis argues that the evolution of modern capitalism was dependent on the prior development of various aspects of measurement including accounting, exact measurement of time, land surveying, weights and measures and city plans. Another such thesis asserts that the development of the modern factory system during the industrial revolution could not have been achieved without the development of accurate and affordable clocks.

In addition, there are a small number of important macroeconomic studies that have estimated a headline figure for the effects of measurement expenditures on the macro-economy. Some of this research has been commissioned in a sister project to the present report, and the reader is also referred to that.

4. Do we need to have a policy, and why?

A widely held view is that public policy is needed to support some parts of the measurement system – metrology in particular. Measurement is treated as one of the *infra-technologies* – the technologies that provide the infrastructure for further innovation. Equally, measurement can also be considered a *general purpose technology*: that is, a technology which will be very widely used, and used for many different purposes, and which also has much scope for improvement.

Economists recognise three particular properties of infra-technologies. First, they are subject to important economies of scale and scope. Second, they are public goods. And third, the private sector left to its own devices would tend to under-invest in infra-technologies, so that government support and co-ordination is required. Moreover, we could add to this list one further feature of infra-technologies that economists often overlook: it is exceptionally hard to measure their full contribution to an economy.

Why is there a tendency towards under-investment? There are two main arguments, which are inter-related.

The first argument concerns **economies of scale and scope**. Research on a particular metrology project involves high fixed costs but the outputs of that project may have quite general applicability for a wide and diverse group of users. The fixed costs may exceed what any one user judges it worthwhile to pay. But the total benefits of the project, added up across all the diverse potential users would justify the fixed cost. It is for this reason that economists argue there is a tendency to under-investment. The total social benefit exceeds cost, but the project is not privately profitable for individual companies or small consortia.

Sometimes it may be possible to form a club or consortium of beneficiaries to share the cost between them. But often the pool of beneficiaries is so diffuse and diverse that it has to be left to a public agency to coordinate and fund the project. And, even if several individual companies and/or small consortia could afford to finance the project for their own benefit, it is uneconomical to duplicate the project in this way. For metrology projects typically have high fixed costs and low marginal costs of disseminating the results to additional users. It is most efficient to fund the project once and coordinate the diffusion of results across all potential beneficiaries.

Case Study – Externalities

Luminanz is a small high technology start up (founded in 2007) which has pioneered a number of light emitting diode (LED) lighting innovations. As well as being much more efficient than conventional lighting– solid state LED lights have long lifetimes (>50,000 hours) which justify their relatively high initial costs.

The efficiency and ageing of LED lights is directly related to the temperature of the LED diode junctions. Accurate measurement of junction temperatures is thus vital to the accurate prediction of lifetimes.

Under the NMS Measurement for Innovation programme the National Physical Laboratory provided a brief consultancy to help it to test and gain confidence in appropriate methods of measuring diode junction temperature.

The company invested significantly in implementing the advice given. The cost to the company in terms of time spent and equipment purchases was estimated at £10,000. The identified commercial benefits were in the order of £250k of GVA - giving a benefit-cost ratio of 18:1.

The second argument is closely related, but couches the argument in terms of **externalities**.

When a single company funds a metrology project itself – and many do – some of the benefits are internal to that company, but there are many potential benefits external to that company. Whenever there are positive externalities of this sort, social benefit exceeds private benefit, sometimes by a very large margin. When that margin is very wide, it is quite possible that a socially valuable project will never seem privately profitable because the externalities cannot be internalised. In this case, private funding will usually entail under-investment.

This argument is most relevant to metrology research projects, because fixed costs are high and the results are of general applicability. As a result, externalities can be very widespread and the margin between social and private benefits may be very wide. Hence, the risk of under-investment is a significant one, and there is an important role for industrial policy.

The argument is least relevant to the day-to-day uses of measurement, because in this case fixed costs are typically lower and the value of the measurement activity is much more specific to an individual user. In this case, externalities are much more limited and the margin between social and private benefits will be pretty narrow. Hence, the risk of under-investment is very small, and there is little need for industrial policy.

There are, however, three other reasons why it may be desirable to have a policy towards metrology and measurement.

First, in some cases, the value of the measurement infrastructure to an individual user is greatest when as many others as possible also use the infrastructure. This is similar to the idea that the value of the internet to an individual user increases as others also use it. Economists use the term 'network effects' to describe this phenomenon: the value of the infrastructure is greatest when the number of users is as large as possible. In this case, there is an additional role for industrial policy to disseminate the benefits of measurement and encourage as many users as possible.

Second, it is sometimes essential that all of the measurement infrastructure should be <u>open</u> and that the ability to make specific types of measurements should not be monopolised by a single company or group of companies. This is relevant in the case noted in Section 2 above, where there is a mismatch between the measurements offered by a supplier and the measurements wanted by a customer. This can happen where a supplier's product does not score well on a particular product characteristic and the seller does not particularly wish to draw attention to this fact. If the ability to measure that characteristic is monopolised by this supplier, then the

Case Study –Public Finances

North Sea oil producers share a common pipeline to convey their oil to shore. The volumes of oil flowing into the pipeline from each platform are measured on the platform and the eventual output is split pro rata so each operator depends on other operators' measurements for the fairness of their particular allocation. Oil is traded by the barrel – a volume measurement. However the flow is measured using a mass flow technique. Converting between mass flow and volume flow involves dividing by density. Density is measured on the platform using pairs of densitometers – normally, oscillatory densitometers.

In 2004, an issue with the accuracy of measurements made with densitometers was discovered by accident. The two densitometers being used on one platform gave different results for the same sample of oil.

A project at National Engineering Laboratory (TUV NEL) resolved the uncertainties. This involved fourteen operators, a densitometer manufacturer, and a calibration laboratory. It found the previous calibration methodology tended to over measure hot oil and under measure cold oil and devised a new improved calibration method.

The cost of the project to the NMS was ~ £200,000. Several parties benefited, as estimated below:

- increased petroleum revenue tax, over 5 years worth - £2,000,000;
- averted cost of legal disputes £500,000;
- avoided cost of private metrology projects in the absence of the joint project £500,000.

Depending on the extent that extra tax has generated extra UK GVA, the cost benefit ratio for the project is between 1:5 and 1:15. As it turned out the taxation effect has been positive for the public purse but increased measurement certainty could have had the opposite effect. Regardless of the direction of the effect, supporting public policy - which includes fair and proper taxation - is part of the rationale for public investment in metrology.

customer will not be able to correct this mismatch. To avoid such cases, it is highly desirable that the measurement infrastructure should always be open and this may call for public funding of metrology to avoid any monopolisation.

Third, and related, there is a long historical tradition that weights and measures should be defined by the monarch or the state, to ensure impartiality and integrity. There has long been a concern that if weights and measures are defined by interested parties on the supply (or demand) side, then this impartiality and integrity may be lost, and that will exacerbate the problems of transaction costs and market failure which accurate measurement is supposed to resolve. This argument is perhaps most relevant to legal metrology, but also to any area where traceability is essential.

A final observation should be made here. It is likely that the role of NMS in supporting innovation in a particular industry will vary over the industry life-cycle. When the industry is in its formative stages, a wide variety of NMS activities may be important. But when the industry is mature, the role of the NMS may be limited to providing reference materials.

5. Where do we have to intervene, and where can we trust the market?

In which areas of measurement is a policy required, and in which can decisions be left to the market? The general guidelines follow the principles of Section 4 above. A policy intervention is most important in those cases where the risk of under-investment is greatest, or when the other three factors noted above (network effects, open-ness and impartiality) are especially important. But in those cases where that risk looks small (and the three other factors are not important), then there is little need for policy.

The risk of under-investment is greatest under the following conditions:

- The ratio of the fixed costs to the marginal costs (for a project) is large
- The applicability of results from a project are highly generic
- The benefits from a project are very diffuse (across many sectors and types of beneficiary)
- The benefits are hard to internalise within a club or consortium

These conditions are inter-related. If applicability is generic then potential benefits are spread over many sectors and beneficiaries and that, in turn, makes internalisation more difficult. And, in turn, these conditions define the cases in which policy intervention is most relevant. In general, it is fair to conclude that the most important area for policy is in metrology research, while there is less need for policy towards the construction of measurement tools, and little or no need for policy towards day-to-day measurement. Moreover, these four conditions can be interpreted as four different features of projects that are **rich in externalities**.

Turning to the other three factors listed above, we can draw some very rough conclusions about the circumstances in which policy interventions are most relevant.

Network effects are typically of two types. *Direct* network effects arise when network members benefit directly from the inclusion of *specific* other members in the network. *Indirect* network effects arise when network members benefit from the supporting products and services that tend to cluster around a well-used network. Direct network effects can sometimes grow without limit as the network expands, while indirect network effects tend to reach an upper limit. This suggests that policy interventions are most relevant where network effects are direct rather than indirect.

Openness is probably most important in the case of 'problem' product characteristics – such as potentially toxic characteristics, or characteristics where products have a history of poor performance. These are the cases where monopolisation of metrology would be most undesirable, as customers would be denied essential measurements.

Finally, impartiality and integrity are probably most important for measurements that are predominantly used for trading between organisations in a market economy, rather than for the internal benefit of an organisation.

6. How do we establish priorities for policy?

As noted before, it is fair to generalise that the top priorities for public funding would be those aspects of metrology and measurement that show the greatest 'public good' character. This argument is strongest for metrology research, but weaker for the development of measurement tools and very weak for day-to-day use of measurement.

But going beyond this broad recommendation, how do we establish specific priorities amongst projects? Which areas of metrology research are most in need of public funding?

One approach to answering this question, described in the main report, identifies some 19 different mechanisms through which metrology projects may impact on the economy. In this approach, metrology professionals are invited to indicate which mechanisms they think are most relevant to each particular project under consideration. When this is done, a model can be used to split the benefits from the project into three broad categories:

- Producer benefits
- Consumer benefits
- Externalities

According to this approach, the top priorities for receiving public support are those where the share of the benefits accruing as externalities is greatest. If two projects each generate an equal share of externalities, then the greater priority will be the one for which the share of consumer benefits is greatest.

The rationale for this method of ranking is that externalities are the hardest form of benefit to internalise while producer benefits are the easiest form of benefit to internalise (in a consortium or club). Accordingly, the priorities for public funding are those where internalisation of benefits is hardest.

While this approach has some attractions, it is difficult and costly to apply in practice. Studies by NIST in the USA have shown that while it is possible to measure the benefits and externalities from measurement, it is costly to do so. That is true for historic projects where the benefits and externalities have already occurred. It is much harder to make such estimates when the projects have not yet taken place and accordingly the benefits and externalities all lie in the future.

The main objection to this method however is that it requires a greater level of investment in assessing the economic benefits of putative projects than the NMS is prepared to make at present.

An alternative to this externalities-centred approach is a criteria-driven approach. This would rank projects using a qualitative assessment of the criteria listed in Section 5 above. Priorities for public funding would be those projects for which:

- The ratio of the fixed costs to the marginal costs (for a project) is large
- The applicability of results from a project are highly generic
- The benefits from a project are very diffuse (across many sectors and types of beneficiary)
- The benefits are hard to internalise within a club or consortium
- The network effects around the measurement infrastructure are greatest
- The risks from closed measurement are greatest
- The impartiality and integrity of measurements is of prime importance

As noted, before, however, this criteria-driven approach is really just a different way of looking at externalities: the first four conditions can be interpreted as four different features of projects that are *rich in externalities*.

Finally, there is one other factor that needs to be born in mind when assessing priorities. The main report shows that there may be an s-shaped relationship between the accuracy of measurement and the economic returns from measurement accuracy. Unless measurement accuracy reaches a certain level, it is hard to generate economic benefits. Then, when a critical level of accuracy is reached, there are rapidly increasing returns to measurement accuracy.

The main report shows a number of examples (Sections 7.3 and 10.1) where there may be such a critical mass. Then, beyond that point, there may be diminishing returns to greater accuracy. In some cases, however, if increases in the accuracy of measurement are matched by increases in knowledge of what to do with the technological potential thus created, then there can be ongoing positive returns to greater measurement accuracy.

These last observations suggest two policy considerations.

First, if there is a critical mass effect, then any policy intervention needs to reach this critical level, or it is barely worth doing.

Second, those projects where benefits from greater measurement accuracy are ongoing will, other things equal, be greater priorities for public support than those for which these benefits are diminishing.

7. How important is metrology compared to other spending priorities?

A full answer to this final question lies well beyond the scope of this report. For it would involve an assessment of how every other publicly funded activity compares with metrology on the seven criteria listed in the last section.

- The ratio of the fixed costs to the marginal costs (for a project) is large
- The applicability of results from a project are highly generic
- The benefits from a project are very diffuse (across many sectors and types of beneficiary)
- The benefits are hard to internalise within a club or consortium
- The network effects around the activity are great
- The risks from 'closed' activity are great
- The impartiality and integrity of the activity is of prime importance

To do that would involve a substantial programme of research spread over all areas of policy, which would be a very large task.

However, we can draw some preliminary conclusions as to how well metrology and measurement scores on these seven criteria.

Referring to criterion (i), it seems clear that much metrology activity involves very substantial fixed costs, while the marginal cost of spreading the benefits of that activity to multiple users is low.

Referring to criterion (ii), some metrology activity generates benefits that are highly generic. That in turn means that benefits are diffuse (criterion iii) and may be hard to internalise as the interested consortium or club will be very large (criterion iv).

The main report discusses the idea that a measurement activity is more important the more numerous are the users of that technique (criterion v). It also discusses the risks of 'closed' measurement (criterion vi) and the need for impartiality and integrity (criterion vii).

In short, metrology is an activity that scores well on the above criteria, indicating that it is an activity requiring public support.

Case Study – Measurement as Infra-technology: Rolls Royce

Rolls-Royce has undertaken an ambitious company-wide case study of the profile and impact of measurement practices using a multidimensional approach. The study uncovered the numerous purposes for which measurement is used, how measuring instruments are calibrated, the benefits from measurement and how measurement activities are managed within this global company. Rolls-Royce uses measurement intensively:

- *in the innovation of new products, design models, materials and manufacturing processes;*
- *at each and every stages of manufacturing;*
- *to support trade with suppliers and end customers;*
- *as part of the product, using sensors to monitor and control engines;*
- *as part of the service offering, using data from monitoring and inspection to manage product throughout its operating life.*

Accurate and timely measurement is therefore crucial to delivering the company's leading-edge engine products and services. This is supported by a sophisticated appreciation of the importance of metrology. Metrology is an actively managed function within the company and the company has a long established measurement training programme. Rolls-Royce maintains an engagement with the UK NMS through advisory bodies that enables it to guide and to some extent shape the NMS agenda in relevant fields of measurement.

With measurement being so extensive and embedded, it is impossible to isolate the benefits of measurement overall. But it is possible to say with certainty that there have been a number of research projects that have delivered better measurement, and these have had benefits far in excess of their costs.

Chapter 2: Metrology and Innovation

(Paul Temple, Department of Economics, University of Surrey, UK)

1. Introduction

The economics literature suggests that the probability of a firm innovating depends upon the technological opportunities open to it, reflected in the 'productivity' of innovation-related search activities. Such opportunities reflect the underlying strength of the science base and the mechanisms which link it to the costs of search – metrology and applied science more generally, and standards being prime examples, as well as supplies of skilled labour.

The purpose of the work underlying this report is to update and extend earlier results concerning the relationship between measurement and the innovation performance of the UK economy, and which were discussed in Temple (2008), which were based upon the findings of the UK version of the 4th Community Innovation Survey (CIS4) which was conducted for the period 2002-2004. This earlier report identified two primary mechanisms for the widespread diffusion of metrological knowledge as:

- Metrological knowledge in the form of published standards made available through the British Standards Institute (BSI). It was found that a large number of such documents contained references to measurement.
- The uptake of services provided by the National Physical Laboratory (NPL), and the role of 'knowledge intermediaries' in measurement knowledge transfer to industry more generally.

To track the latter, unique data made available by NPL allowed for the services supplied by NPL to be mapped onto the industry of purchase.

It was found that many of the firms purchasing NPL services belonged to technical testing laboratories and consultancies, as well instrument manufacturers.

Using the Community Innovation Survey, it was possible to show that firms in these industries were particularly likely to be strong product innovators. Arguably this suggested that innovation in the economy more generally is linked to the National Measurement System via the use of product innovations which embody knowledge acquired more generally through taking measurements and making use of instruments as well as standards.

The main body of the 2008 report considered the strength of both these channels for the probability that a firm in a particular sector is an innovator.

Both the stock of standards and the extent of standard use appeared to be jointly important in determining product and process innovation; while standards seemed to be important for product innovation, the extent of instrument use seemed to be important for both product and process innovation.

The study went on to consider further dimensions of innovation outcome, conditioned on the firm being innovation active. Firms in industries where measurement was important were particularly likely to regard product oriented outcomes, market entry, and cost reduction as important effects of innovation.

It was also found that firms in industries with a large stock of standards were likely to place a higher value on the information content of "technical, industry, or service standards", while firms in industries which made large use of instruments were likely to place a higher value on information emanating from suppliers. This evidence was consistent with the economic significance of two knowledge diffusion channels identified above.

2. Updating the Results from CIS4 – Measurement and Innovation

The first objective of the 2009 report was to update the results obtained from CIS4, using the survey conducted for 2004-6 (CIS5) as a check on their continuing relevance and for other comparative purposes. However in a second stage, this report also considered the linkages between innovation and actual performance outcomes, utilising data from both these two surveys, exploiting the fact that a considerable number of survey respondents have featured in both CIS4 and CIS5, allowing for the creation of a so-called 'panel.'

The empirical analysis combined information on both channels identified in the earlier study – the extent of instrument use and standard use across 97 industries – into a single variable intended to proxy the strength of an industry's linkages with the National Measurement System. The combined indicator of 'measurement intensity' was constructed from the quartiles of each variable, allocating any given industry a score of 0 if it is in the lowest quartile, 1 if it is in the second quartile and so on, and then adding this to the score on the second variable. Some 12 industries are in the upper quartile by both measures giving a summed score of 6, the maximum. These industries both make much use of instruments and are supported by a strong collection of standards.

Regression models of each of the five innovation measures of innovation contained in the surveys were used to provide estimates of the marginal probabilities associated with the measurement intensity indicator. Using a variety of controls for other influences on the probability that an individual firm is observed as innovating, such as firm size or its sector, it was possible to show that the measurement intensity variable had a detectable impact on the probability of a firm being an innovator, in both the CIS4 and CIS5 samples. This is true for each of five definitions of innovation contained in either survey. For the later CIS5 sample for example the estimated impact is not only positive but statistically significant on innovation at conventional levels – at better than 1% for the probability of innovation activity, both categories of product innovation, as well as process innovation. The positive marginal probability for novel process innovation is also statistically significant but only at the 5% level.

The impact of 'measurement intensity' on the probability of various types of innovation is summarised in the chart below (Figure 1), for both the CIS4 and CIS5 samples, and when both samples are combined ('pooled') but where allowance has been made for differences between the surveys in the aggregate incidence of innovation.

These marginal probabilities indicate the *change* in the probability of observing the dependent variable in question of a one unit change in the independent variable. As noted above, the construction of the measurement variable allows for a simple interpretation of the marginal probabilities involved. For example, consider the impact on product innovation (prodinov). Looking at the pooled data, we can see that a hypothetical firm (alike in all other respects) experiencing a richer measurement environment - corresponding to one quartile of the distribution of either the standards stock or the extent of instrument use in its industry – shows an increase in the probability of its being innovation active of around 0.024. This is slightly less than that reported for innovation activity (0.026). The marginal probability associated with novel product innovation (prodinov) is considerably less than this (0.015) but this is still greater than for either category of process innovation, of any kind (procinov - 0.010) or for novel process innovation (procnov - 0.003). However, it should be noted that the % of firms in the overall sample in these latter categories is much smaller, so the *proportionate* effects involved (elasticities) are correspondingly much higher.

It can therefore be seen that the effect of being in an industry with effective linkages to the NMS is particularly strong for product innovation. It can also be observed that the effect on innovation is very similar across the two surveys, which is what might be expected for a longer term 'structural' feature of the UK economy.

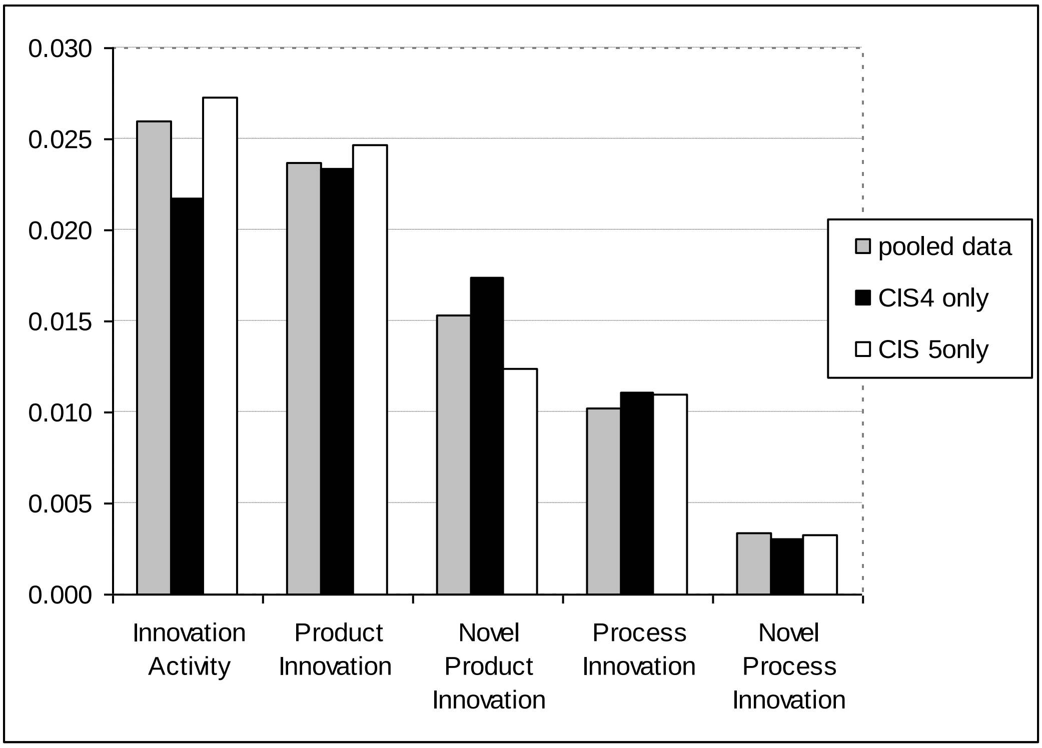

Figure 1. Marginal Probabilities based upon measurement intensity of industry

3. An Econometric Model of Firm Level of Productivity

Having estimated the impact of the measurement indicators on the probabilities of observing a firm innovating in the first stage of the project, it was then possible to assess the impact of the occurrence of innovation on firm level productivity growth, using the time series data available across the two innovation surveys, thereby establishing a link between the NMS and productivity performance.

Any impact of a firm's 'own' innovation on its own almost certainly represents a considerable underestimate of innovation on productivity growth since it ignores the contribution of what economists term knowledge or technology 'spillover' effects – contributions to productivity growth which stem from knowledge generated outside the firm and not from the knowledge generated by its own process of innovation. Among the very many empirical studies of productivity growth, it has become a stylised fact that the link between knowledge generating activities such as R&D and productivity effects becomes clearer as the degree of aggregation increases: e.g. the link is stronger at the industry level than at the firm level and stronger at the country level than at the industry level. This statistical evidence strongly suggests the presence of spillover effects (see for example Audretsch 2002 who argues that this is partly explained by the dynamic role of small firms as captors of spillovers in an innovative economy). Indeed, the channels identified in the report provided potentially very important mechanisms through which such spillovers are actually captured.

In considering the impact of own innovation on own productivity, there is an important distinction to be drawn between product and process innovation. While successful *process* innovation may be expected to have an impact on productivity within the firm, it is far from clear that conventional measures of productivity will pick up such a similar effect, for example, when, within a supply chain, an upstream product innovation, results in downstream productivity improvement by firms using the innovation. While in principle the quality improvement involved could be picked up via an appropriate quality adjusted price index, such indices do not exist at the firm level. Nor are the price indices available at the industry level, which might to some extent mitigate the problem, able to deal with the beneficial effects from enhanced access to variety which innovation and product differentiation.

Attempting to estimate the impact of actual innovation on productivity ignoring the temporal dimension to innovation by looking at the cross section contained in a single survey is fraught with difficulties of interpretation, often of a 'cause or effect' variety. For this reason, econometric analysis based upon panel data, the recording of the innovation activity at the level of the individual firm in one period and then observing the growth that occurs between that period and the next, is likely to be more informative. In the context of this study, this meant considering observed innovation in the earlier Community Innovation Survey (CIS4) as a predictor of productivity growth (along with other factors such as investments in both physical and human capital). In fact, the link between innovation and productivity at the firm level proved difficult to establish. This is inevitable because of the uncertainty attached to innovation itself.

Product Innovation Case Study – Selenium.

Work at the Laboratory of the Government Chemist provides a sound basis for measuring vital elements in the diet – with long-term benefits for public health that could be enormous. Meanwhile a novel LGC measurement method has enabled Hughes Mushrooms - is one of the UK's largest and most innovative suppliers of mushrooms, with established expertise in growing mushrooms with elevated levels of selenium - to back claims for its health foods through a scientific study led by a nutrition expert.

Selenium is believed to be deficient in the UK diet, with decline in recent decades attributed to increased consumption of wheat from Europe in place of North American wheat. This has led to the search for effective means of increasing intake through Se-enriched functional foods.

LGC's work in showing how inductively-coupled plasma mass spectrometry (ICP-MS) could enable accurate measurement of the different forms of Se is a good example of how results from basic measurement science can be used directly in commercially important R&D. The costs of the Hughes Mushrooms R&D exercise are confidential, and so is Hughes's turnover and profit from selling high-Se mushrooms, but we calculate the ratio of cost to discounted increased profit as 1:12.

But other reasons include the fact that not only are spillover effects important, but quite possibly the lion's share of the impact of innovation is a spillover effect on productivity *outside* the innovating firm. Indeed this was an important result established some years ago by Paul Geroski using the SPRU innovation data set, when he found that it was innovations used, rather than innovations produced, that seemed to contribute most to *industry* level productivity growth. Moreover he also found that it was innovations used, originating from the engineering sector (which includes instruments), which were particularly important.

The current work chimes with Geroski's conclusion that (his results) "suggest that flows of knowledge emanating from Engineering might repay closer examination" (Geroski 1991). This report provides some of that work, and the role played by instrument makers (a component industry of the engineering sector) in the context of measurement is probably just part of a much larger genus in which it is the use of product innovation which drives much productivity growth.

Despite these difficulties, some tentative estimates were established, with as much as 10% additional growth in own labour productivity over a four year period being attributable to novel process innovation, while there may be a smaller contribution from product innovation. Moreover, the use of additional information in the earlier survey (CIS4) concerning respondent's views regarding the effects of innovation (as to both strength and direction) suggests that successful innovation in terms of own productivity needs be considered alongside complementary investment in the creation of capacity.

The effects of certain types of process oriented innovations, whose purpose may be to provide a better service for customers, appear to result in negative productivity growth, although as with product innovation, there may be considerable productivity gains for customers. This highlights the problem of not being able to observe a firm's prices, correctly adjusted for quality changes.

Chapter 3: NMS and science

(Michael King, University of Manchester, UK)

NPL Publications

The *Web of Science* database provides a convenient source of data on journal papers produced by NPL and other institutions. This database is not exhaustive but covers papers published in all the major journals at least back to the 1970s. Hence, any paper indexed by the Web of Science (WoS) is likely to be of a reasonably high quality.

On average around 75 papers from NPL are published in WoS journals each year but it can be seen that this has varied considerably over time. Between 1974 and 1995 the annual flow of papers declined by around 60%. However, after 1995 the supply of papers grew by around 10% per year, reaching 159 in 2008.

Though the flow of new journal papers from NPL has varied widely over time, NPL's research has focussed on applied physical science:

- Instrumentation, optics, spectroscopy and medical imaging
- Electronics and engineering
- Materials science and metallurgy

Finally, the top 10 subjects account for over 75% of NPL's papers, although there is a long tail of other subjects that NPL contributes towards.

The significance of NPL's contribution to the UK's research in these subjects is given in Table 1. This gives the proportion of UK papers, on a given subject, that were produced by NPL. It can be seen that NPL consistently contributes most significantly to research into instrumentation (3.8%) and metallurgy (2.4%).

Table 1: Percentage of UK papers produced by NPL

Subject Area	1970s	1980s	1990s	2000s	mean
Instrumentation	4.2%	4.1%	3.0%	3.9%	3.8%
Applied Physics	1.9%	1.7%	1.2%	1.4%	1.5%
Materials (Multidisciplinary)	1.2%	1.2%	0.7%	0.8%	0.9%
Optics	5.2%	1.9%	0.8%	0.9%	1.5%
Metallurgy	2.3%	3.0%	1.9%	2.5%	2.4%
Physical Chemistry	1.1%	0.5%	0.3%	0.7%	0.6%
Electronics	0.7%	0.6%	0.4%	0.6%	0.5%
Radiology & Medical Imaging	0.6%	0.7%	0.5%	0.5%	0.6%
Spectroscopy	2.7%	1.1%	0.8%	0.9%	1.2%

Engineering (Multidisciplinary)	0.4%	1.3%	1.0%	1.6%	1.3%

Table 2 gives the proportion of NPL's papers that were produced in collaboration with universities, companies or other leading NMIs (NIST in the US; PTB in Germany; and BIPM in France). It can be seen that NPL's collaboration with UK universities and other NMIs has grown considerably:

- In the 1970s only 8% of papers involved collaboration with universities, whereas now 28% involve co-authors in UK universities.
- In the 1970s only 1% of papers were written in collaboration with other leading NMIs, whereas now around 10% involve co-authors in PTB, NIST or BIPM.

Table 2 : Percentage of NPL's Papers Written in Collaboration with Other Organisations

Collaborator	1970s	1980s	1990s	2000s	mean
UK University	8.3%	10.7%	21.7%	28.1%	17.3%
UK Firm	2.5%	3.1%	3.5%	4.4%	3.4%
NIST , PTB or BIPM	1.2%	2.5%	6.4%	9.5%	5.0%

Benchmarking the Quality of NPL's Papers

The (academic) quality of NPL's research has varied over time. Citation statistics can be used to compare NPL's papers against similar papers from other UK institutions (mainly universities). The analysis uses papers on instrumentation. NPL's steady stream of papers on instrumentation amounts to a significant fraction of the UK total.

Data

Records of all UK instrumentation papers published between 1974 and 2008 were extracted from the Web of Science database (12,000 observations). The key variables are: times cited (y); age in years (t); and number of cited references (r).

Results and Interpretation

There are two data generating processes at work: one for whether a paper has the chance to receive any citations at all (Inflation Model), and another how many citations it receives given the chance (Negative Binomial Model). The results from estimating these two models are now discussed.

The main findings from the "inflation" part of the model were as follows:

- A paper is vastly more likely to have no citations if it is one or two years old respectively, and highly significant. This implies that that likelihood of not being cited is around three times as high for papers in their first or second year as for later years.

- Papers are much less likely not to be cited if they cite other papers in the literature. It was found that the likelihood of being cited decreases by around 70% for every cited reference that the paper contains.

The main findings from negative-binomial part of the model were as follows:

- Doubling the age of a paper doubles the number of citations it will have received. However the rate of citations declines by around 6% a year.
- There is evidence that citing other papers in the literature tends to increase a paper's citation rate but that the effect decreases as the bibliography grows.

As expected, the citation rate varies greatly across subjects. If an instrumentation paper is also relevant to analytical-chemistry or spectroscopy, then the citation rate is much higher than average but if a paper's second subject is computer hardware or particle physics, then the citation rate is much lower than average.

The findings suggest that the impact of NPL's instrumentation papers on science has varied over time: in the 1970s and 1980s NPL's papers had a far higher citation rate than comparable papers produced by UK universities, but there was a significant decline in NPL's relative citation rate during the 1990s. However, in recent years there has been a sharp improvement. Currently the impact of NPL's papers on academic science matches that of comparable papers from UK universities.

The variation in NPL's relative citation rate may reflect changing priorities and beliefs about what NPL's role should be. In particular, the drop in the citation rate (and indeed the number of papers) may have been due to policy makers at the time discouraging NPL from replicating the work of universities. Anecdotal evidence from discussions with NPL's staff suggests that the production of papers was not seen as a major priority during the 1990s and was done more as a matter of individual interest.

However, in recent years there has been a renewed emphasis on quality of science and benchmarking, stimulated by the NMS policy unit. For example, publication data is now included in the annual performance report that NPL's management supplies to the department. Hence, the sharp increase in the quantity and quality of journal papers may be part of a growing recognition that journal papers are a useful vehicle for disseminating new knowledge.

NPL's Input to Different Fields of Science

The set of papers that cite NPL's articles can be classified by subject area. Hence, it is possible to investigate the flow of information into different fields of science. This was done by finding the fraction of NPL's citations that were received from papers in a specific subject area.

It was found that NPL supports a core of 25 subject areas; these account for over 90% of all NPL's citations. These subject areas are not mutually exclusive and a paper typically has around three associated subjects. Hence, it is convenient to group the subjects into five broader fields of science: Materials Science; Physics; Chemistry; Instrumentation & Optics; and Engineering.

The information below shows the fraction of citations received from papers in each of these fields. It can be seen that NPL's degree of support differs slightly across these fields:

- Materials Science accounts for 27% of NPL's citations
- Physics accounts for 29% of NPL's citations
- Chemistry accounts for 18% of NPL's citations
- Instrumentation & Optics accounts for 23% of NPL's citations
- Engineering accounts for 24% of NPL's citations

Fraction of NPL's Citations that were received from Papers in a given Subject Area

It was found that a high proportion of NPL's research feeds into Materials Science and Metallurgy. In particular, around 20% of NPL's citations come from multidisciplinary Materials Science. Moreover, the impact on Materials Science seems to have grown significantly since the 1970s. In contrast the fraction of citations received from other fields of science appears to have remained relatively constant.

A surprisingly low fraction of citations came from Instrumentation: 20% of NPL's papers are on Instrumentation but less than 10% of NPL's citations were received from Instrumentation papers. This may be because research on Instrumentation feeds into other fields, in a way that research on a subject like Metallurgy probably doesn't.

Knowledge Flows

It was possible to investigate the flow of knowledge from the subjects that NPL publishes into the subjects that NPL's research feeds into. The table below provides a heat map for the strength of the connection: the rows correspond to the 25 subjects that cite NPL's papers and the columns correspond to the 10 subjects that NPL publishes in.

A subject tends to feed strongly into itself; this can be seen from the "heat" of the diagonal cells. However, there is also a strong interaction between certain subjects:

- Physical Chemistry feeds into a wide range of subject areas. Its greatest impact is on Material Science / Metallurgy and Applied Physics / Thermodynamics.
- Electronics has a relatively narrow impact. The most significant impact is on Instrumentation, Optics and Applied Physics. Materials Science and Chemistry are the most unresponsive fields.
- Multidisciplinary Engineering has a very similar impact to that of Electronics (but smaller in scale).
- Instrumentation has a very broad impact; feeding in to most subject areas. The most significant impact is on Optics, Electronics and Applied Physics. The breadth of the impact is indicative of a cross-cutting technology.
- Optics has a very similar impact to that of Instrumentation (but is smaller in scale).
- Nuclear Medicine and Medical Imaging has a very narrow impact. The most significant impact is on Nuclear Technology and Acoustics. Chemistry and Materials Science are unresponsive.
- Spectroscopy feeds into Physical Chemistry, Atomic Physics and Applied Physics. Engineering and Materials Science seem unresponsive.
- Multidisciplinary Materials Science feeds into most subject areas. The most significant impact is on Metallurgy, Applied Physics, Condensed Matter and Physical Chemistry.
- Metallurgy has a very similar impact to that of Multidisciplinary Materials Science.
- Applied Physics feeds in to virtually all subject areas. The most significant impact is on Instrumentation and Optics.

	CHEMISTRY, PHYSICAL	ENGINEERING, ELECTRICAL & ELECTRONIC	ENGINEERING, MULTIDISCIPLINARY	INSTRUMENTS & INSTRUMENTATION	OPTICS	RADIOLOGY, NUCLEAR MEDICINE & MEDICAL IMAGING	SPECTROSCOPY	MATERIALS SCIENCE, MULTIDISCIPLINARY	METALLURGY & METALLURGICAL ENGINEERING	PHYSICS, APPLIED
CHEMISTRY, PHYSICAL	2507	19	29	198	97	37	350	331	217	499
CHEMISTRY, MULTIDISCIPLINARY	411	14	11	35	27	7	100	57	19	82
CHEMISTRY, ANALYTICAL	353	8	15	119	39	7	79	50	38	160
ACOUSTICS	0	151	4	88	5	182	0	5	0	27
ENGINEERING, ELECTRICAL & ELECTRONIC	94	725	187	690	327	48	22	73	38	510
MECHANICS	106	14	40	114	48	0	0	194	129	109
ENGINEERING, CHEMICAL	465	5	7	29	10	0	10	70	43	26
ENGINEERING, MECHANICAL	97	8	43	70	30	5	4	186	140	54
ENGINEERING, MULTIDISCIPLINARY	32	58	163	317	53	4	4	53	25	191
MATHEMATICS, APPLIED	0	0	12	11	0	0	0	0	13	0
NUCLEAR SCIENCE & TECHNOLOGY	108	0	0	385	14	217	94	53	41	152
INSTRUMENTS & INSTRUMENTATION	100	405	338	1737	347	75	93	101	17	1167
RADIOLOGY, NUCLEAR MEDICINE & MEDICAL IMAGING	13	78	4	184	7	507	36	0	0	42
OPTICS	37	310	261	731	1501	11	70	56	5	715
SPECTROSCOPY	202	33	9	224	140	45	310	33	14	209
MATERIALS SCIENCE, MULTIDISCIPLINARY	1343	65	76	139	86	5	38	1649	1623	517
METALLURGY & METALLURGICAL ENGINEERING	1070	10	5	12	0	0	7	965	1630	220
POLYMER SCIENCE	77	4	4	11	11	0	12	80	8	11
NANOSCIENCE & NANOTECHNOLOGY	161	17	75	76	23	0	10	199	195	104
MATERIALS SCIENCE, COATINGS & FILMS	285	5	22	74	19	0	68	240	97	229
PHYSICS, APPLIED	650	392	197	1178	549	29	157	490	183	1727
PHYSICS, CONDENSED MATTER	470	77	28	119	87	5	89	327	181	486
PHYSICS, MULTIDISCIPLINARY	124	75	37	210	206	16	71	64	51	277
PHYSICS, ATOMIC, MOLECULAR & CHEMICAL	211	45	12	132	252	41	141	67	10	248
THERMODYNAMICS	781	5	22	129	15	0	3	20	44	117
Total	5535	1624	960	4227	2837	849	1273	3613	3242	4810

NPL's Contribution to Research Carried Out by UK Companies

It was possible to search for papers by UK companies that cited NPL's papers. It was found that 4.1% of UK papers were written by UK companies (usually in collaboration with universities). These papers are a consequence of R&D carried out by UK firms and are of particular relevance to future R&D activities. The uptake of NPL's research can be investigated using citations from UK companies. It was found that around 7.6% of NPL's citations from UK papers were from UK firms.

During the last 35 years, researchers based in 130 UK companies wrote 310 articles that cited NPL's papers (9 pa). Over the same period UK firms wrote a total 63,000 papers. Therefore, around 0.5% of the articles produced by UK firms made use of NPL's research. If these articles are representative of firm's wider R&D activities, then this suggests that around 0.5% of private R&D efforts make direct use of information from NPL's papers. This gives an estimate of NPL's contribution to technological innovation by UK firms.

At first sight this figure may appear small but it can be grossed-up to give an idea of the corresponding economic value. Previous research found that:

- The elasticity of labour productivity with respect to the intensity of innovation is around 0.5. That is, doubling the level of innovation related activity would eventually lead to a 50% increase in productivity.
- An increase of 0.10% in the UK's labour productivity amounts to an increase of £110m pa in output.

Hence, an increase in private R&D efforts of 0.50% would lead to an increase in labour productivity of 0.25%; this amounts to an increase in output of around £275m pa. This gives an estimate of the annual growth in GVA that is probably underpinned by NPL's research.

Of the 130 companies that cited NPL's papers, 50 of them cited NPL two or more times, and were responsible for 75% of the citations that NPL received from UK companies (details are given in the Appendix). Finally, it was found that these 50 companies are particularly research intensive - producing around 50% of all the papers written by UK companies.

A large fraction of NPL's direct contribution R&D is absorbed by firms in the following sectors:

- Paints, dyes and coatings (18%)
- Other chemicals (17%)
- Metals and metallurgy (13%)
- Electronic Equipment (13%)
- Aerospace (12%)
- Scientific instruments (11%)

However, sectors vary with regard to the volume of papers produced. Chemicals and Pharmaceuticals produce a particularly large number of papers; whereas, relatively few papers are written by firms that develop specialist engineering software.

NPL Downloads: Measurement Good Practice Guides

As well as writing journal papers NPL also produces short practical guides on how to carry out accurate measurements and quantifying uncertainties. These reports are very different in flavour from that of academic articles but are another important type of codified knowledge. This section analyses data on the extent to which reports were downloaded from NPL's website between November 2005 and July 2007.

Download statistics provide a measure of the extent to which knowledge, generated by NPL's research activities, filters into the economy. It has been found that around 2,200 documents are downloaded from NPL's website each year by UK based users. Moreover, around 10,000 documents are downloaded annually by non-UK users. These figures show that not only does UK-industry make use of information from NPL but also that the information is of sufficient importance that firms in other countries seek it out.

However, though there is a wide range of publications offered on the website, the bulk of downloads are accounted for by Measurement Good Practice Guides (MGPGs). The site offers users a choice of around 1,100 documents that can be downloaded for free but the vast majority of these publications receive very few downloads. Moreover, if documents are placed in descending order of the number of downloads they have attracted, then the top 30 documents account for over 60% of all downloads. That is, the top 5% of documents account for over half of all downloads. Hence, the impact from NPL downloads comes from a small core of key documents, the majority of which are in three areas: (1) Materials, (2) Engineering and Process Control, and (3) Dimensional Metrology. The findings suggest that compared to other areas, these three have a significant impact via Measurement Good Practice Guides (MGPGs).

What drives the demand for MGPGs? There is evidence that MGPGs function as quasi-standards. That is, they function much like the formal standards published by the British Standards Institute (BSI). Firstly, over 30% of BSI standards are measurement related and sometimes cite MGPGs. Secondly, there is anecdotal evidence that companies adopt MGPGs and use them as internal company standards (employees are encouraged to refer to them when carrying out tests). Certain sectors of the economy have to operate to a high level of precision, such as aerospace, in order to comply with standards and regulations. Hence, the level of demand for a MGPG is determined by whether it is on a subject that is of interest to sectors where measurement dependent standards are important.

Conclusion

This chapter has analysed the degree to which NPL contributes to UK science through the production of journal papers. The conclusions are as follows:

- NPL contributes strongly to measurement science and materials science - NPL supplies around 3.8% of the UK's instrumentation papers and 2.4% of the UK's metallurgy papers.
- There was a marked decline in the supply of journal papers from NPL during the 1980s and 1990s. However, in the last 10 years there has been a rapid increase in NPL's publication rate: in 1995 NPL's scientists produced around 40 journal articles p.a., whereas at present NPL's publication rate is around 160 journal articles p.a.
- There has been a sustained increase in collaboration with UK universities and foreign NMIs: in the 1970s only 2% of papers were written in collaboration with academics whereas now the fraction of collaborative papers is near 30%.
- The findings suggest that the impact of NPL's instrumentation papers on science has varied over time. In the 1970s and 1980s NPL's papers had a far higher citation rate than comparable papers produced by UK universities, but there was a significant decline in NPL's relative citation rate during the 1990s. However, in recent years there has been a sharp improvement so that, at the present time, the impact of NPL's papers on academic science matches that of comparable papers from UK universities.
- EPSRC currently spends £29m p.a. on research in the field of instrumentation. It was found that these grants generate around 90 papers p.a., which suggests that the average cost of producing such a paper is approximately £320k. At present around 30 instrumentation papers are produced by NPL each year (20% of NPL's total) and so producing a similar volume of papers using researchers based at UK universities would cost the EPSRC around £10m pa.
- A high proportion of NPL's research feeds into Materials Science and Metallurgy. In particular, around 20% of NPL's citations come from multidisciplinary Materials Science. Moreover, the impact on Materials Science seems to have grown significantly since the 1970s. In contrast the fraction of citations received from other fields of science appears to have remained relatively constant.

- A surprisingly low fraction of citations came from Instrumentation: 20% of NPL's papers are on Instrumentation but less than 10% of NPL's citations were received from Instrumentation papers. This may be because research on Instrumentation feeds into many other fields.
- Around 9 citations a year are received from UK firms.
- Around 7.6% of NPL's citations, from UK based authors, were from researchers in firms R&D labs. This is large, given that firms produce only 4.1% of the UK's papers.
- Around 0.5% of the articles produced by UK firms cite NPL's papers. This gives an estimate of the fraction of private R&D efforts that are underpinned by NPL's research.
- Around 2,200 documents are downloaded from NPL's website each year by UK based users.
- The impact from NPL downloads comes from a small core of key documents. The majority of downloads come from the three areas: (1) Materials, (2) Engineering and Process Control, and (3) Dimensional Metrology.

Case Study-Science. Dissemination through MGPGs

Good Practice Guides are topic-based documents produced by NPL and delivered either in hard copy or electronically. The guides are aimed at technicians, scientists and managers. They have a chatty, approachable, style.
One such guide is 'Fundamentals of Good Practice in Dimensional Metrology', a document whose production was funded by the NMS. Taking this popular Guide as an example, the download data show 153 downloads of this guide into the UK over a 15 month period we studied. The nature of this particular guide is that it will mainly be used for training.
One way of estimating the value of a guide's use in training is to equate it with extra practical experience. The extra experience looks to be about two years' worth – which we believe to be worth 5% of salary. Another valuation method is given by the observation that absorbing the contents of a typical guide is equivalent to attending a five day training course. The cost of such a course would be £1k and the foregone productive time lost would be worth a similar amount. Assuming fully loaded industrial salaries for qualified staff to be in the order or £40k both methods indicate a training value of £2k. With the figures above, the overall benefit would be £600,000. The direct cost to the NMS of producing and publishing the guide was approximately £40,000. This gives a minimum benefit:cost ratio of 15:1.

Chapter 4: Economic performance impacts

A Productivity Model - Mixed Modes of Innovation

Mixed modes of innovation are a set of activities that are jointly undertaken and form a specific strategy or routine of firms. They represent combinations of complementary assets and investments together with types of product, process or organisational innovation. That is, unusually, the model treats inputs, outputs and linkages in the innovation system as jointly determined and mutually dependent.

Modes of innovation are derived through factor analyses of micro data. This is a statistical technique that enables a large set of survey variables to be efficiently expressed as a small set of indicators. Factors have the convenient property of orthogonality, which leads them to be good variables for explanatory equations, as they do not suffer from collinearity.

The research results reported here are based on exploratory multivariate analyses which provide a relatively parsimonious technique for deriving modalities of innovation that show the integration and complementarities between ranges of inputs, outputs and interfaces in the innovation process. This section provides an overview of the advances made towards formulating typologies of mixed modes of innovation.

The model is designed to:

- Take account of non-technological innovation including organisational and strategic change.
- Treat "innovation", investment and knowledge links as jointly determined.

Typology of Modes

The common patterns – typologies of modes of innovation – derived from the factor analyses are :

- IP/technology innovating
- Marketing based innovating
- Process modernizing
- Wider innovating
- Networked innovating

Impact of Metrology on Productivity

The productivity equation using the modes to succinctly represent the innovation strategies and their combinations, pursued by sets of firms, can be used as a test bed for the impacts of other economic variables, including those determined or heavily influenced by public policy. The example of this application of the model considered here is to assess the role of the National Measurement System (NMS). This is the programme of public expenditure to support the pure and applied science of metrology and the development and dissemination of new and improved principles and applied techniques of measurement. It covers largely but not exclusively physical phenomena, such as mass, length, time, flow, electricity, chemical composition, pollution, radiology and many other fields.

The NMS is a major part of the technology infrastructure of the economy, providing the codified knowledge that underpins most types of production activity, scientific research and international trade. There have been a number of approaches over recent years to quantification of the economic impact of the NMS. Most of these have focussed on measurement as an input to business innovation, where it clearly does have a role in enabling new and better products and processes via for example, the ability to include a wider set of characteristics in a product's specification as their properties can be reliably measured. But measurement has a broader role – for example it is extensively applied in public services, including for example forensic science, and in the private sector good and traceable measurement is essential to business as usual and to incremental improvement and cost minimisation.

In the recent paper on the economic rationale for a publicly funded NMS, summarized in Chapter 1 of the report, Peter Swann has noted that measurement can be reasonably regarded as a General Purpose Technology, with a pervasive and continuously improving role. From this perspective it can be positioned in economic models as a general enabler of growth and productivity. It is therefore feasible to incorporate measurement indicators in equations that explain productivity, as an alternative formulation to identifying its effects indirectly through product and process innovation.

The productivity equation using the modes to represent innovation is ideal for this purpose, as a variable for the importance of measurement can be entered independently of the innovation indicators.

The variable used here has been developed by Paul Temple of Surrey University and is an ingenious construction based on two proxies for the availability of measurement knowledge to a firm. One of these is the stock of standards relevant to an industrial sector and the other is the purchases by that sector of scientific and precision instruments. A high proportion of written standards refer directly to a measurement technique or research finding, while the scientific and precision instrument sector is known to be one of the main direct users of the services and research findings of the national measurement institutes and thus embeds that knowledge in new and improved equipment. Together standards (a net stock indicator) and instruments purchases (a flow indicator) provide access for industry to the codified knowledge resulting from measurement science funded by the NMS.

Case Study. Metrology and Productivity. Case Study 3G Networks

Third generation 3G mobile phone technology carries large amounts of data quickly so users can view stream video and access the Internet from their handset. 3G was a significant step up from earlier systems, which had limited data capacity and were designed primarily for voice. The capital cost of setting up each of the four new high bandwidth networks was between £5bn and £10bn.

An important novel component in 3G networks was a new type of variable tilt antenna, capable of handling higher aggregate data volumes and higher network transmission speeds whilst controlling the potential interference effects by directing the RF signals only to the region of interest. However there were many different antennas available and it proved difficult for network planners to evaluate the best option because specifications were set by the manufacturers themselves, rather than verified by an independent organisation.

The NMS antenna range, housed in an anechoic chamber facility at the National Physical Laboratory was able to provide full information about how the antennas could be expected to behave, including their gain and directivity. Makers' measurement uncertainties were found to be typically 5%, while the NMS facility was able to achieve 2%. Improved measurement could improve estimates of key performance parameters by as much as 1db.

Experts who were involved in 3G network planning estimate that substantial efficiency savings were made possible through quite subtle changes in network topology: fewer base stations needed in rural areas, lower masts, less interference between adjacent base stations in urban areas etc.

Mobile phone networks account for more than 1% of all UK electricity usage, so any improvements in network efficiency would also contribute to substantial energy savings (possibly worth in the order of £1m, annually) and associated carbon reduction.

Experts have estimated that the calibration data improvements supplied by the NMS measurements could equate to a 1% one off saving in network capital costs and a comparable saving in operational costs for the lifetime of the network.

Since each UK 3G network cost between £5bn and £10bn to establish, the benefits of this work are therefore very high. A simple and very conservative calculation gives a benefit/cost ratio (in terms of additional economic surplus) of 25:1.

Temple's variable summarises these two sources, for 97 sectors, by the sector's position in the quartile ranges of the standards' stock and equipment purchases. Thus a sector in the upper quartile for both proxies will score 6 while a sector in the lowest quartile for both will score 0. This variable is exogenous to the innovation survey data used to build the basic model. Each firm in the survey is attributed the measurement score appropriate to its main sector.

In the summary of the Paul Temple paper at chapter 2, it is noted that the direct impact of innovation on firms' own productivity appears relatively weak, but Temple points out, very important effects of innovation might be expected to appear outside of the innovating firm itself, through "spill-over" effects from the availability of new knowledge. In the impact model described here, some aspect of measurement knowledge spillovers – are captured by observing the stock of such knowledge at sector rather than individual firm level, but relating this knowledge stock to firm performance.

The results of estimating the productivity equation with the measurement indicator (called comb score) are shown in Table 3 below.

Table 3 : Productivity Equation Estimated with Measurement Variables

VARIABLES	LPROD06	DLTURN	LPROD06	DLTURN
Innovation Indicators	-	-	-	-
PII1	-0.011	0.075***	-0.007	0.076***
	(0.042)	(0.027)	(0.042)	(0.027)
PII2	0.118*	0.146***	0.129**	0.148***
	(0.060)	(0.035)	(0.059)	(0.035)
PII3	-0.019	0.033	-0.023	0.034
	(0.040)	(0.023)	(0.040)	(0.023)
PII4	-0.012	0.072***	-0.010	0.071***
	(0.034)	(0.020)	(0.034)	(0.020)
PII5	-0.007	0.012	-0.006	0.010
	(0.045)	(0.026)	(0.045)	(0.026)
comb_score	0.076***	0.013		
	(0.014)	(0.009)		
_Icomb_scor_1			0.041	0.076
			(0.181)	(0.074)
_Icomb_scor_2			0.188	0.100
			(0.177)	(0.069)
_Icomb_scor_3			0.487***	0.110
			(0.177)	(0.069)
_Icomb_scor_4			0.510***	0.094
			(0.178)	(0.069)
_Icomb_scor_5			0.472**	0.170**
			(0.189)	(0.079)
_Icomb_scor_6			0.480***	0.146*

In Table 3 the dependent variables are the log of the productivity level in 2006; log of t the change in turnover 2004 – 2006 and the log of the change in employment, 2004-2006. PII1 to PII5 are the innovation modes variables. The full model includes sector, regional and foreign market dummies (not shown here). The use of a log version of the dependent variables enables the coefficients on the metrology indicators to be interpreted as elasticities, so that the potential effects on productivity of a higher measurement knowledge stock can be estimated directly from the equations and the "benchmark" values of the dependent variables.

It is important here to bear in mind that the measurement indicators represent the access to the stock of knowledge, not the flow of new knowledge from current expenditure on measurement research and dissemination i.e. it is the economic value of accumulated investment over many years. Further calculations are required to generate the potential effect on national income of a change in the level of current NMS spending on measurement activities and research.

The measurement score variables are highly significant in the productivity equation's dependent variables. The size of the coefficient would suggest an 8% change in labour productivity for moving one unit on the measurement score (e.g. from 3 to 4, or 4 to 5). A 1% change is indicated for growth in sales, but that is not statistically significant. However, these findings have to be interpreted with caution, since a unit change represents a large number of standards and/or a large increase in the use of the instruments that embody new measurement knowledge, on a scale that may seem unrealistic. But they can be taken to indicate the potential for additional investment in developing and propagating measurement knowledge to have substantial effects on economic performance.

Columns 3 and 4 in the table show the results of treating the metrology indicators as a set of dummy variables, which bring out the effects of different levels of measurement knowledge in each of the quartiles of the distribution across firms in the innovation survey.

These results show that the main productivity impacts of higher levels of knowledge are recorded higher up the measurement intensity scale. That is, building on existing measurement knowledge intensity shows quantitatively more productivity enhancements than bringing up lower levels of such knowledge. This intensity effect is most notable when growth is taken as the dependent variable. Then the positive role of measurement knowledge is significant only for the two top quartiles.

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