Research Policy 38 (2009) 583–589

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Developing science, technology and innovation indicators: What we can learn from the past

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ARTICLE INFO

Article history:
Available online 14 March 2009

Keywords:
Science, Technology and Innovation (STI)
R&D Data
Indicators
Economic Measurement
Statistics

ABSTRACT

The science–technology–innovation system is one that is continuously and rapidly evolving. The dramatic growth over the last 20 years in the use of science, technology and innovation (STI) indicators appears first and foremost to be the result of a combination of, on the one hand, the ease of computerized access to an increasing number of measures of STI and, on the other hand, the interest in a growing number of public policy and private business circles in such indicators. Such growing interest might be expected in societies that increasingly use organised science and technology to achieve a wide variety of social and economic objectives and in which business competition is increasingly based on innovation. On the basis of 40 years of indicators work, we argue that frontiers and characteristics of STI indicators that were important last century may no longer be so relevant today and indeed may even be positively misleading.

1. Introduction

Like any other statistics, indicators of science, technology and innovation (STI) can be both used and *ab*used. The dramatic growth in their use is the result of the interaction between supply and demand. The ease of computerized access to an increasing number and variety of measures of STI has facilitated a constructive response to the growing demand from both public and private organisations for statistics that might be helpful to them in their work, often involving the use of science and technology to achieve practical as well as economic objectives.

Competition at the level of nations, industries, firms and individuals has stimulated this demand for comparative STI indicators. However, abuse of these indicators may arise, on the one hand, from straightforward ignorance of the sources, definitions and methods used for their collection and publication, and, on the other hand from a sort of STI version of Goodhart's law[1]: once STI indicators are made targets for STI policy, such indicators lose most of the information content that qualify them to play such a role. Particularly over the last decade with the growing trend towards the use of bibliometric indicators for target setting in higher education research and the use of aggregate country-wide indicators with respect to research and development (R&D) expenditures as a % of gross domestic product (GDP) such as the European 3% Barcelona target, the effects of Goodhart's law are likely to be significant.[2] Furthermore, as in other cases of composite indicators such as GDP, STI indicators are likely to be strongly subject to a composition bias: 'the drunk searching for his missing keys under the lamppost' effect—i.e. indicator developers will tend to concentrate (first) on developing indicators of those things that are easiest to measure, which may not be the variables most pertinent to STI policy or management. Up to a level, the evolution of STI indicators can be read as a story of searching in progressively 'darker' places as our 'key-detection' antennae become more finely attuned over time.

Already in use in the science and technology research community over a much longer period, STI indicators have today become an essential ingredient in research on the modes of operation of the science–technology–innovation sub-system itself and its relationship with the wider social and economic system. In societies that allocate large sums from both the public and private sectors for such things as (experimental) R&D, new software tools and programmes, technical support services, the design and development of new products and processes, it is inevitable that policy-makers, private businesses and financial investors as well as researchers will wish

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[1] See Goodhart (1975). Suppose some social statistic is correlated with good things—such as a knowledge society with high R&D investments or university research quality with a high excellence ranking of universities. Once being declared to be an important measure, and that one wants to increase it, one will reduce the correlation. "The reason is that we will tend to affect the statistic in the cheapest and simplest ways, which are probably going to be those which artificially inflate the statistic without addressing the problem it is supposed to measure. The correlation measured "in the wild" and the correlation once we start targeting this statistic will usually be different." (http://patrissimo.livejournal.com/343159.html).

[2] For a recent analysis, see Van Pottelsberghe de la Potterie (2008).

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doi:10.1016/j.respol.2009.01.018

to have available quantitative statistical tools to control the scale of commitment and learn more about the effectiveness of these activities. It is also quite understandable that they would wish to make comparisons between countries, organisations (public and/or private) and industries in the direction, scale and efficiency of their commitments. This does not mean, of course, that qualitative assessments of various kinds should be either neglected or ignored.

In this sense, the national development of STI statistics from the early National Science Foundation surveys in the US in the nineteen fifties fits the natural desire to measure national STI investments and to compare countries' relative performance in such areas as science, technology and innovation. However, the measurement of STI investments is not an easy matter. Even simply to record the expenditures on personnel and equipment *inputs* to the R&D process is by no means as easy as it may appear at first sight, and international comparisons are beset by numerous problems, as 40 years of painstaking OECD harmonisation work bears witness to. The measurement of the *outputs* of the system is even more difficult and will always remain controversial.

This means that it will be essential to use STI statistics in full awareness of the "footnote" problems that do arise as a result of differences across countries in definition, classification and measurement of most STI indicators. In the world of STI statistics the possibilities for abuse, given the often endogenous impact of such statistics on public S&T spending itself, are numerous and much more obvious. This holds not only for STI performance assessment at the level of individuals or organisations, but also at the level of countries. One might for example remember the way that some comparisons made in the 1970s and 1980s between the so-called socialist economies and the OECD countries[3] ignored many of the substantial differences in definitions between R&D in the West and in the East. Today, there are somewhat similar problems in making comparisons between the developed, emerging and other developing countries in comparing STI indicators.[4]

Given our combined average age of 72 and our experience in the field over the last 45 years, we thought it could be useful to reflect upon the long-term development and use of STI indicators, and especially R&D measures, as we have witnessed those over the last decennia.[5] After all, not only has R&D now become one of the most well-known acronyms amongst S&T policy makers and researchers, it has also achieved "general purpose" fame, both as policy target and as an object of economic analysis.

2. On economic (mis-)measurement: "*plus ça change, plus c'est la même chose*"

Obviously problems of definition and measurement are not unique to the science, technology and innovation system. Some 12 years ago, one of us at a meeting celebrating the fiftieth anniversary of ISTAT, the Italian statistical agency, wrote the following: "Economics has sometimes been called by other social scientists the "queen" of social sciences because of economists' superior ability to measure and quantify the main variables of economic activity. Indeed, the motto of the econometrics society "*science is measurement*" could be said to characterize the ascent of at least that part of the economics profession this century to the more applied sciences. The superior ability of economists to measure, for example, a number of key aggregate variables (growth, labour force, unemployment, productivity, inflation) has led to widespread policy acceptance of such concepts during the post-war period. At the same time, new concepts (total factor productivity, the "NAIRU", long-term unemployment as well as a range of alternative monetary variables) have been quickly developed and integrated into policy research, often without the interminable conceptual debates so typical of the other social sciences. Finally, it could be argued that with the end of the cold war and the demise of the socialist, planned economic model, alternative economic concepts have now also disappeared from the international statistical yearbooks. The final supremacy of the market model therefore appears to some extent reflected in the complete policy convergence of harmonized aggregate economic concepts and measures. All this benefits the growing number of users of such statistics; no longer confined to central government and planning agencies or university research institutes, but including now also many private financial institutions, consulting and advisory firms and other organisations and individuals." However, as was also noted: "...users and above all policy makers have gone too far, much too far in their "belief" in the true value of such harmonized aggregate economic concepts and proxies. Increasingly, there is a discrepancy between the total reliance; one could say the "fetishism" of macro-economic policy making for such aggregate economic concepts and the growing mismeasurement of economic production, its rate of growth and "real" improvement in economic welfare." (Soete, 1996).

In short, even the most basic economic concepts such as GDP, one of the most widely-used economic indicators in the world, are beset with problems in their measurement, especially now that services account for between 60 and 80% of total output in most developed countries, and in making international comparisons across countries despite the use of purchasing power parity adjustments.[6] No one really knows how to measure the output of such sectors as health, education, or government services themselves, sectors which account for large fractions of GDP in many countries. In fact *input* measures are often used as a surrogate for *output* measures in these areas. The problems are even greater when it comes to the least developed countries, in which greater parts of the economy are in subsistence agriculture and household activities, where few market transactions are involved. This does not mean that all measures of economic activity are useless, but it certainly does mean that they must be used with great care and in full awareness of their limitations and of the stage of evolution of the particular economies and societies that are being considered and compared. This point is still insufficiently recognized in many international comparisons, as is evidenced by regular, sometimes dramatic revisions to individual countries GDP.[7]

The natural sciences, too, have their problems of measurement, especially in areas such as astronomy and geology where large errors have been made in the past (Easlea, 1973). However, progress has been made by devoting continuous attention to the improvement of measurement systems with great success. One may wonder

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[3] See amongst others Radosevic (1999).

[4] See amongst others Bell (1984) and Dahlmann et al. (1987) on the NICs, the then "newly industrializing countries", and Cassiolato et al. (2003) on the current set of large emerging developing countries, the so-called BRIC countries.

[5] In this sense our analysis is complementary to the historical analysis of Godin (2003–2007, 2007), more based on our own personal "endogenous" participation and perception of the development of STI indicators over the last 45 years.

[6] Whereas the use of such internationally harmonized PPP adjustments has corrected for differences in inflation rates between countries, their use across the board (for example for international comparisons of R&D expenditures or other productivity performance measurements) raises many questions. One of the first papers written by Soete (1975) was a comment on an OECD proposal for a new method to deflate R&D expenditure (OECD, 1975). Such relatively old questions about the misuse of PPP are today exacerbated by new economic discussions (Neary, 2004) about intrinsic biases in PPP, likely to overstate the income convergence across poor and rich countries as compared to nominal exchange rates. One major reason for this is that increasingly large quantities of intangible internationally traded goods are available across the world at similar prices reflecting intellectual property compensations in poor as well as rich countries.

[7] See amongst others the attempts at re-measuring China's GDP output over a long historical period by Maddison (2007).

whether measurement in the social sciences will ever be quite as accurate. In most social sciences it still appears to be difficult to achieve such reliable improvements, despite the rapidly growing opportunities for computer-based data collection and behavioural experiments mimicking controlled environments under laboratory conditions. The emergence of strategic behaviour as a result of the policy use of such new measures might, however, as Goodhart's law suggests, undermine the actual measurement value of such indicators. Keeping an open and critical mind particularly with respect to the most commonly used indicators with the aim of continuous improvements of STI measurement is therefore an absolute must. For sure, smart people will always find new ways of playing the 'improved' indicators so that they, too, ultimately might lose their policy utility. In this sense, indicators research might well resemble, with its continuous search for further improvement, a form of 'Red Queen' escalation activity trying to stay ahead of policy abuse.

3. Measuring STI: the early years

The OECD, in close interaction with its members' statistical offices, has been particularly influential and constructive over the last 40 years in developing international standards for research and development measurement and in stimulating and improving input and output measurement of both R&D and other services. Together with others at the OECD, in particular Yvan Fabian and Alison Young, one of us part of those early discussions in the 1960s on the inclusion or exclusion of particular activities in the *Frascati Manual*[8] OECD (1981) (Freeman, 1962, 1967, 1969; Fabian, 1963; Freeman and Young, 1965). It appeared particularly difficult to separate research and experimental development activities from the broader spectrum of scientific and technological services (STS) concerned with providing support for R&D, disseminating the results, applying new knowledge in various ways, and producing and selling new products. Not surprisingly, organisations that were engaged in research and experimental development were often also engaged in such STS activities as well. The *Frascati Manual* tried to distinguish between research and experimental development and related scientific activities. The latter included such activities as general scientific library, information and documentation services; training and education of research workers in specialised educational institutions such as universities; general purpose data collection, for example routine geological and geophysical survey work, mapping and exploration activities, routine oceanographic survey work, daily meteorological records, monthly production statistics, collection and arrangement of specimens for museums, zoological and botanical gardens; routine testing and standardisation activities, and also design and engineering activities.

The main theoretical criterion in the Frascati scheme for the separation of the R&D function from related scientific activities was the distinction between *novelty* and routine.

"In so far as the activity follows an established routine pattern it is not R&D. In so far as it departs from routine and breaks new ground, it qualifies as R&D. Thus, for example, the collection of daily routine statistics on temperature or atmospheric pressure is not R&D, but the investigation of new methods of measuring temperature or the investigation of temperatures under circumstances in which they have never been previously recorded (for example, outer space or the interior of the earth) *is* research. Likewise, the publication of a book which simply records daily information on the temperature or pressure is not R&D, but general purpose data collection. The systematic analysis of these recordings with a view to explaining long-term changes in climate, or the possible effects of changes in ocean currents, *is* research activity. To take another example: in the field of medicine, routine general autopsy on the causes of death is *not* research, but special investigation of a particular mortality in order to establish the side effects of certain forms of cancer treatments *is* research. Routine tests on patients, carried out for doctors, as for example, blood tests and bacteriological tests, are *not* research. But a special programme of blood tests in connection with the introduction of a new drug *is* research." On the basis of this criterion, most of the activities of central government testing and standardisation institutes, major scientific libraries and information services, museums and geological and meteorological survey organisations became *excluded* from research and experimental development as routine-based scientific activities. Also excluded were many scientific and technical activities at the enterprise level, including consultancy, project feasibility studies, much design and engineering, production engineering and quality control as well as training and information services.

Viewed in retrospect, the distinction between novelty and routine seemed relatively straightforward in the early 1960s. Since then, however, new sectors such as the software industry have emerged in which this distinction is more difficult to make and likely to lead to an under-reporting of research in certain sectors, particular service sectors. These factors are relatively important in considering science–technology systems that are either in a process of very rapid growth ("explosion") such as the emerging economies today or at that time Japan and the European countries witnessing a rapid post-war catching up process of economic growth, or science and technology systems in a process of rapid contraction ("implosion"). In the case of "exploding" systems, whilst almost all STS are expanding, there is an increasing concentration on R&D and some re-classification of STS activities in this direction. R&D expenditures typically increase much more rapidly than personnel. On the other hand, in the case of "imploding" science–technology systems, as was the case after the collapse of the Soviet Union and the end of the centrally planned economies in Eastern Europe, a process of involuntary contraction of R&D activities was set in motion. In all those countries, there was an abrupt fall in R&D activities in the 1990s, sometimes by more than 50%. However, the fall in expenditure was much greater than the fall in personnel and according to some accounts, many of those employed in what were once (and sometimes still are) Research Institutes or R&D Departments became engaged in a variety of other STS activities either part-time or full-time, such as consultancy, teaching, computer services, information services, design work or production engineering.[9]

4. The rise and fall of industrial R&D

Behind the international attempt at measuring research and experimental development in the Frascati Manual was a recognition that most efforts to generate discoveries and inventions had become centred in relatively specialised private and public institutions in the "Research and Experimental Development" Network. While the wider spectrum of scientific and technological services that linked the R&D system with production and other technical activities was considered essential for efficient innovation and often predominated in the diffusion of technical change in many branches of industry, it was the professional R&D laboratory and the activities carried out there that were the characteristic of the industrial S&T system as it emerged over the late 19th and 20th century. Although

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[8] The document stipulating the methodology for collecting and using statistics about research and development in countries that are members of the Organisation for Economic Co-operation and Development.

[9] For an account of the state of affairs in the Soviet economy *before* this fall, see Glaziev and Schneider (1993), and OECD, Centre for Cooperation with the Economies in Transition (1994). For an analysis of the situation *during* and *after* the implosion see Piech and Radosevic (2006a,b), Radosevic (2006), and Radosevic and Reid (2006).

government and university laboratories had existed earlier, it was only in the 1870s that the first specialised R&D laboratories were established in industry (Bernal, 1953; Beer, 1959).

The professional R&D system was barely recognized by economists,[10] despite their recognition that "something" (a residual, or a measure of our ignorance) was behind most of the economic growth of the United States in the 20th century and the post-war period in particular. Yet long before the 20th century, experimental development work on new or improved products and processes had been carried out in ordinary workshops.[11] However, what became distinctive about modern, industrial R&D and justified the focus in the Frascati Manual on this concept was its scale, its scientific content and the extent of its professional specialisation. A much greater part of technological progress appeared attributable to research and development work performed in specialised laboratories or pilot plants by full-time qualified staff. It was this sort of work that one wanted to get officially recorded in R&D statistics. It was totally impracticable to measure the part-time and amateur inventive work typical of the nineteenth century. In short, present R&D statistics are really a measure of the professionalisation of this activity, the professional recognition of R&D activities as a separate activity carried out by professional researchers.

Much of the subsequent research at the Science Policy Research Unit, at Yale, Reading, Stanford and other centres of research on innovation highlighted the fact that the extent of such R&D specialisation and professionalisation should not be exaggerated. Important inventions were still made by production engineers or private inventors. With every new process, many improvements were made by those who actually operated those processes. In some firms "Technical" or "Engineering" departments or "OR" sections were set up, the function of which was to intermediate between R&D and production and which often contributed far more to the technical improvements of an existing process than the formal R&D department, more narrowly defined. The thorough study by Hollander (1965) on the sources of increased efficiency in Du Pont rayon plants is a good illustration of these points. But even viewed in retrospect, the focus on R&D seemed justified. It was the specialisation of the R&D function which justified such expressions as the "research revolution" (Silk, 1960) to describe what happened in twentieth-century industry. Industry associations of R&D managers were created in different countries,[12] and most large industrial firms in the industrialised countries set up their own full-time specialised R&D sections or departments.

The expression "technology", with its connotation of a more formal and systematic body of learning, really only came into general use when the techniques of production reached a stage of complexity where traditional knowledge of "arts and crafts" no longer sufficed. The older arts and crafts actually continued to exist side by side with the new "technology". Nevertheless, there was an extremely important change in the way in which knowledge of the techniques used in producing, distributing and transporting goods became ordered. Some people call this change simply "technology", to distinguish those branches of industry that depend on more formal scientific techniques than the older crafts. However, in many cases very sophisticated industries, such as aero-engines and instruments, used also craft techniques and vice-versa. Consequently, the division of industries into "high", "medium", or "low" technology categories usually came to be based on a measure of R&D-intensity rather than an examination of process technology. Such a categorisation can hence provide only a very rough description. These changes are also reflected in the patent statistics for the various branches of industry. In mechanical engineering, for example, applications from private individuals are still important in comparison with corporate patents; in electronics and chemicals, by contrast, they are very few.

To summarize, over the last century formal R&D expenditures rose gradually to become the most widely used measure of technological performance of countries, of sectors and of firms, even though many other supporting activities would fall outside of the narrow Frascati R&D definition.

5. From R&D to innovation

In the 1970s and 1980s there was a substantial increase in the resources devoted to the study of the STI system itself, especially in the United States and the United Kingdom. Although the community is still small, several dozen individuals and a few organised groups in a variety of universities began to specialise in this field of research. Moreover, many governments had begun to follow the example of the NSF in conducting regular surveys of R&D activities. In industry too, management research began to focus on STI as a source of comparative strength. The results flowing from these new streams of research increasingly influenced the measurement and interpretation of STI indicators. 'Innovation' began to receive far more attention and the definition of industrial R&D was increasingly criticised as being too restrictive. In particular, empirical research showed that 'design' and the detailed engineering activities associated with original design were essential features of industrial R&D in many different industries, although by no means always conducted within departments or groups formally designated as 'R&D' departments.

The dissatisfaction with R&D as an "industrial research and experimental development" input indicator was not confined, however, to the omission of engineering, design and other STS activities. After the early SPRU and Yale innovation surveys,[13] it became clear that the actual industrial locus of innovation could well be far upstream or downstream from the firm or sector that carried out the research. Some of our closest colleagues, such as the late Pavitt (1984), Rothwell (1977) and Townsend (1976), had been at pains for many years to stress the much more complex sectoral origin and nature of innovation, than the one assumed in the simple but popular technological classification of industries into 'high', 'medium' and 'low' R&D intensity. There is by now a large literature on the

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[10] With little reference made to R&D by any of the early growth economists such as Solow (1957), Denison (1962) or Jorgenson (1963).

[11] As we noted elsewhere: "The classical economists were well aware of the critical role of R&D in economic progress even though they used a different terminology. Adam Smith (1776) observed that improvements in machinery came both from the manufacturers and users of machines and from "philosophers or men of speculation, whose trade is not to do anything but to observe everything". Although he had already noted the importance of "natural philosophers" (the expression "scientist" only came into use in the nineteenth century), in his day the advance of technology was largely due to the inventiveness of people working directly in the production process or immediately associated with it: "a great part of the machines made use of in those manufactures in which labour is most subdivided, were originally the inventions of common workmen" (Smith, 1776, p. 8). Technical progress was rapid but the techniques were such that experience and mechanical ingenuity enabled many improvements to be made as a result of direct observation and small-scale experiment. Most of the patents in this period were taken out by "mechanics" or "engineers", who did their own "development" work alongside production or privately." This type of inventive work still continues today and it is essential to remember that it is hard to capture it in official R&D statistics (Freeman and Soete, 1997, pp. 7–9). A good example of this is the financial sector, where a lot of innovation has gone on over the last 20 years, little or none of it captured in innovation statistics, let alone R&D statistics, even though there is much (high quality) 'research' going on in financial institutions. See Beunza and Stark (2004) on the highly innovative, but peculiar valuation that takes place in arbitrage in the trading room.

[12] In Europe in 1966 the European Industrial Research Management Association (http://www.eirma.org/) was set up.

[13] See amongst others Pavitt et al. (1987) on the SPRU innovation data survey and Levin et al. (1984) on the Yale innovation survey.

weaknesses and biases of sectoral classifications for STI indicators, which we will not discuss here.[14]

Such dissatisfaction with R&D indicators was at the centre of the successful development of a new set of STI output indicators within the framework of the *Oslo Manual* (1992) and of the various surveys carried out since then under the joint initiative of the OECD, Stats Canada and Eurostat. The surveys being carried out today not just in OECD countries but also in emerging and developing countries such as China, Brazil, India, South Africa, Argentina, and Chile have opened up new research avenues to the measurement of innovation, as well as providing new opportunities for micro-based evidence research linking the individual firm innovation survey data to other firm level performance data.

Again it is impossible to do justice here to the innumerable academic research papers, PhDs, policy papers that have been written on such innovation survey data and innovation indicators. As in the case of the development of harmonized industrial R&D statistics within the *Frascati Manual*, we would claim that the development of harmonized, innovation-output indicators within the framework of the *Oslo Manual* was a central factor behind both a better understanding of the science and technology system[15] and the changing nature of the innovation process itself as emphasized by many of our colleagues in the '90s.[16] According to David and Foray (1995), innovation capability had to be seen less in terms of the ability to discover new technological principles, and more in terms of the ability to exploit systematically the effects produced by new combinations and uses of components in the existing stock of knowledge. Not surprisingly the new model appeared more closely associated with the emergence of various new sorts of knowledge "service" activities, implying to some extent, and in contrast to the Frascati R&D focus, a more *routine* use of the technological base, allowing for innovation without the need for particular leaps in science and technology, something that has also been referred to as "innovation without research" (Cowan and Van de Paal, 2000, p. 3).

One could argue that this model brings into the debate the particular importance of STS activities as it now puts a stronger emphasis on access to state-of-the-art technologies. While 'fuelled', so to say, by the Internet and broadband, this mode of knowledge generation, based in David and Foray's (1995, p. 32) words "on the recombination and re-use of known practices", does, however, raise much more extensive information-search problems as it is confronted with impediments to accessing the existing stock of information that are created by intellectual property right laws.

Not surprisingly at the organisational level, the shift in the nature of the innovation process also implied a shift in the traditional locus of knowledge production, in particular the professional R&D lab. The old system was based on a relatively simple dichotomy. On the one hand there were the knowledge generation and learning activities taking place in professional R&D laboratories, engineering and design activities, of which only the first part was measured through the *Frascati Manual*; on the other hand there were the production and distribution activities where basic economic principles would prevail of minimizing input costs and maximizing sales. This old system is still very much dominant in many industrial sectors ranging from chemicals to motor vehicles, semiconductors and electronic consumer goods, where technological improvements at the knowledge-generation end still appear today to proceed along clearly agreed-upon criteria and with a continuous ability to evaluate progress. The largest part of engineering research consists of the ability to "hold in place" (in Richard Nelson's words): that is, to replicate at a larger industrial scale and to imitate experiments carried out in the research laboratory environment.

The recent David and Foray model of technological progress is associated with service activities with, for example, the continuous attempts at ICT-based efficiency improvements in the financial and insurance sectors, the wholesale and retail sectors, health, education, government services, business management and administration. This model is much more confronted with intrinsic difficulties in replication. Learning from previous experiences or from other sectors is difficult, sometimes even misleading. Evaluation is complicated because of changing external environments: over time, among sectors, and across locations. It will often be impossible to separate out specific context variables from real causes and effects. Technological progress will, in other words, be based more on 'trial and error' yet without, as in the life sciences, providing "hard" data that can be scientifically analysed and interpreted. The result could be that technological progress will be less predictable, more risky and ultimately more closely associated with entrepreneurial risk-taking.

If the first shift in our understanding of innovation involved removing the dichotomy between R&D and production, the second shift has removed (at least partially) the distinction between production – as a locus for innovation – and consumption. The notion of user-driven innovation, originally developed by innovation scholars such as Lundvall and his group in Aalborg in the late 1970s (Lundvall, 1985), has now taken on much more importance and been used by Von Hippel (2004) to explain the rise of open-source software as well as new developments in sports equipment. Such innovation reduces risks for individual entrepreneurs, as the risk of developing an unsuccessful technology is spread across the many user-producers who contribute and perhaps implement their own ideas.

6. Conclusions: "*Recherche sans frontières*": national statistics measuring global impacts

Economically, the world has witnessed astonishing growth and transformation over the last 40 years. Economic development has been spurred by the opening up and ensuing expansion of world trade and by the dramatic reduction in barriers to capital movements. However, it is only fair to say that either in conjunction with such liberalisation or separate from it, the growth externalities of knowledge have had a lot to do with the rapid post-war growth of the OECD countries. First, under the form of a technological and consumption catching-up first by the European countries and Japan – the 30 glorious years ("les trentes glorieuses", as Keith Pavitt would quote Jean Fourastié (1979)) – and subsequently by the newly industrialising East Asian economies. The third phase, which was set in motion in the late 1990s with the world integration of the large emerging economies such as Brazil, Russia, India and China,[17] could be said to be still in full swing, requiring a much longer period of global adjustment over another 30 years or so.

STI indicators today play, in interaction with these shifts in global demand, a crucial role in national policy debates about science, technology and innovation. Many economists[18] now believe that the largest part of world-wide growth and development over the last 10 years has been associated with an acceleration in the diffusion of technological change and world-wide access to codified knowledge. The role of information and communication technologies has been instrumental here, as has been that of more capital-

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[14] See Malerba (2004) for an overview of recent work in this area.

[15] As in the form of postmodern science (Funtowicz and Ravetz, 1993, 1999), strategic science (Rip, 2002) or co-produced science (Callon, 1999).

[16] At the risk of omitting some, one may think of Gibbons (1994), David (1996), Lundvall and Johnson (1994), Foray (1998), Edquist and Texier (1998) and many others.

[17] Compared by Richard Freeman (2005) with a doubling of the world labour force.

[18] For overviews see amongst others Archibugi and Lundvall (2001).

and organisational-embedded forms of technology transfer such as foreign direct investment, which is today as a percentage of GDP a decimal point greater than 40 years ago as well as being no longer confined to the OECD world. There remains, of course, a huge worldwide concentration of R&D investment in a number of rich OECD countries, but it is important, certainly from a national STI policy perspective, to realize that such activities, whether privately or publicly funded, are increasingly becoming global in focus: in other words, "*research without frontiers*".

The EU originally expected private firms to contribute substantially to the so-called 'Barcelona target' of 3% of GDP to be invested by 2010 by member states in R&D, providing two-thirds of the funds needed to attain this norm. However, most private firms were not interested in increasing R&D expenditure just for the sake of it or to meet an externally imposed target. They hoped rather to develop new production technology concepts and new products responding to market needs, to improve their own efficiency or to strengthen their global competitiveness. Given the much higher risks involved in developing such new products for global markets, firms today will often prefer to license such technologies or alternatively to outsource the most risky parts to small high-tech companies, which operate at arms length but can be taken over, once successful. Not surprisingly in most OECD countries, the large R&D-intensive firms appear today less interested in increasing their R&D investments at home than in rationalising them or where possible reducing the risks involved in carrying out R&D by collaboration with others, sometimes through publicly sponsored or enabled programmes (SEMATEC and IMEC in micro- and today nano-electronics), or perhaps through so-called 'open innovation' collaboration.

The central question, and one already analysed in the 1990s for the OECD countries by input–output economists such as Mohnen (1996), appears to be whether the benefits of knowledge investments can be appropriated domestically or whether they will "leak away" globally. In the catching-up growth literature (for example Fagerberg, 1991; Verspagen, 1991), it was emphasized that catching up by lagging countries depended very largely on the import and transfer of technology and knowledge, both formally and informally (Radosevic, 1996). As a logical extension, in the current global world economy, it seems obvious that increasing R&D investment is unlikely to benefit only the domestic economy. This holds *a fortiori* for small countries, but it is increasingly valid for most countries in the world. Thus, as Meister and Verspagen (2004) pointed out, achieving the 3% Barcelona target in the EU by 2010 would ultimately not reduce the income gap between the EU and the US, the benefits of the increased R&D efforts accruing not only to Europe but also to the US and the rest of the world. In a similar vein, Griffith et al. (2004) illustrated how the US R&D boom of the '90s had major benefits for the UK economy and in particular for those UK firms that had shifted their R&D to the US. For example, a UK firm shifting 10% of its R&D activity to the US from the UK while keeping its overall R&D expenditure at the same level, would witness an additional increase in productivity of about 3%, an effect of the same order of magnitude "as that of a doubling in its R&D stock" (Griffith et al., 2004, p. 25). In short, the link between the location of "national" firms' private R&D activities and national productivity gains appears today to be increasingly tenuous.

It is here, we would claim, that the broadening of the STI concept to include "innovation" with its much stronger local links towards growth and development dynamics is particularly relevant, offering significant new policy insights. From a global growth and development perspective, it is no longer the impact of the transfer of industrial technologies on economic development that should be at the centre of the debate, but rather the broader organisational, economic and social embedding of such technologies in a development environment and the way they unleash or block specific development and growth opportunities. That process is much more complex in a developing country context than in a developed country one. As is now recognized in the endogenous growth literature,[19] in a high income, developed country context, the innovation policy challenge seems increasingly directed towards questions about the sustainability of processes of "creative destruction" within environments that give a premium to insiders, to security and risk aversion, and to the maintenance of income and wealth. In an emerging developing country context, by contrast, the challenge appears directed towards the establishment of industrial technological competitiveness through more traditional industrial science and technology policies including the support for engineering and design skills and for accumulating "experience" in particular. Finally, there are the majority of developing countries characterized by "disarticulated" knowledge systems, well described by many development economists in the area of science and technology (for example Bell, 1994; Sagasti, 2004) and where the endogenous innovation policy challenge is most difficult of all, and which neither time nor space allows us to address here.

The science–technology–innovation system is one that is continuously and rapidly evolving. As we have tried to show, frontiers and characteristics that were important last century may no longer be so relevant today and indeed may even be positively misleading. Research on STI indicators appears today as challenging as ever.

Acknowledgements

We are grateful to critical comments received from three anonymous referees as well as the editor of this journal as well as from Fred Gault, Louise Earl and Michael Kahn. Any remaining errors are our own.

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[19] This view of the philosophy and aims of innovation policies differing among countries according to their level of development, which is reminiscent of many of the arguments of the old 'infant industry' type, has now become popular in the endogenous growth literature. See Aghion and Durlauf (2005).

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