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FRAMING EMERGING NANOTECHNOLOGIES: STEPS TOWARDS A FORWARD-LOOKING ANALYSIS OF SKILLS

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FRAMING EMERGING NANOTECHNOLOGIES: STEPS TOWARDS A FORWARD-LOOKING ANALYSIS OF SKILLS [1]

How can we think about the implications of radical technological change for employment and skills? Given the long lead-times required to train professionals, this is an important question, and standard approaches to modeling employment and occupational trends only provide limited parts of the answer. Innovation studies provide us with some further tools for tackling the question, such as diffusion and industry life-cycle analysis, and ideas about different sorts of technological change (including technical paradigms, regimes, and trajectories of change), which are very relevant to emerging technologies like nanotechnology. There are many claims and much argument about the scope and speed of the evolution of nanotechnology. It poses particular challenges to conventional forecasting approaches precisely because it is difficult to resolve such debates in the infancy of a technology, and in this case knowledge is fragmented because of the intersection of numerous lines of development at the nano-scale. Current skill and employment projections for nanoindustries are problematic, so it is important to consider new ways to improve understanding and provide more policy-relevant intelligence.

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Keywords: emerging technologies, nanotechnology, statistics, Foresight, skills.

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[1] This paper draws on materials published in Russian as I. Miles (2010) 'Nanotechnology Foresight: How can we explore Employment and Skills Implications?' Foresight-Russia. Vol. 4, No 1, pp. 20 – 36 and Gokhberg L., Kuznetsova I., Dalin V., Fursov K. (2011) 'Nanotechnology Statistics in Russia: formation of a new field'. Issues of Statistics (Voprosy Statistiki). No 6. P. 3–19.

Introduction

Forecasting the development of major new technologies is notoriously difficult. The major trajectories of underpinning technologies may be fairly evident (as in the famous case of Moore’s Law for microelectronics), but this requires that we have enough experience with these technologies for such trajectories to have been established and become detectable. Even if this is the case, timescales and break-points in trends are challenging to foresee. Industry commentators are often surprised by the outcome of completion among platforms and standards (which is not solely determined by technical factors); while the applications to which the technologies are put and the systems in which they are embedded often surprise the original innovators. As observed by Niels Bohr (and often attributed to Yogi Berra) “Prediction is difficult, especially about the future”,[2] we might add “and about emerging technologies”. The very fact that we label something “emerging” means that it is far from fully visible and often seems to be very promising.

Contemporary Foresight practice (e.g. see: Georghiou et al., 2008, Gokhberg, Sokolov, 2013) recognises that it is frequently inappropriate to focus on a “most probable” future. When we confront disruptive change, conventional ways of estimating likelihood break down. It is important to explore alternative futures, to gain a better grasp on the range of contingencies which might plausibly emerge. Contemporary Foresight also stresses combining participative or interactive approaches with more formal forecasting and futures techniques (e.g. see Meissner, 2013). This reflects awareness that future-relevant knowledge and capacity to act are distributed phenomena. They are not entirely decentralised, let alone evenly distributed across societies, of course: each is concentrated in specific locations. Not only is it that knowledge and capacity to act may be localised in different sites. Knowledge is fragmented across numerous disciplines, professions, practitioners, and economic agents for example (consider knowledge of fundamental sciences, of various fields of technology application, or ethics and regulatory frames, of markets and marketing, and so on.) For Foresight to be both well-grounded and effective in shaping action, these conditions have to be recognised: which means establishing frameworks that engage broader communities. Formal forecasting and modelling approaches have their place, but they are only some of the inputs to a wider Foresight process that will need to access knowledge that is widely distributed.

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[2] A short discussion on the origins of this statement appeared in the Economist (Letters to the Editor, 15 July 2007). Online: http://www.economist.com/blogs/theinbox/2007/07/the_perils_of_prediction_june (accessed 02/07/2013).

Few organisations possess wide-ranging knowledge about the factors whose interplay shapes the main contours of the landscape of future possibilities. The conventional response – convening an expert panel – can provide invaluable inputs. The panel will need to be constructed so as to capture a sufficient range of knowledge. This often means going beyond the standard pool of expertise drawn on by an organisation, so Foresight resembles "open innovation" in having substantially broader engagement than has been usual in more limited forecasting and futures work. Furthermore, other stakeholders may dismiss recommendations which flow from the "usual suspects" as simply echoing established frameworks and sectional interests. Panels need to be constituted to take into account perceived legitimacy and practical capability. Furthermore, panels should often be supplemented by techniques designed to engage wider pools of participants in providing information, creating visions, and exploring implications. Among the latter techniques methods that go beyond just "disseminating results", but that allow for substantive engagement and interaction, such as Delphi surveys (polling large numbers of people), consultation processes and workshops, scenario workshops, and similar techniques.

Capacity to act also varies widely, across various spatial levels and sector-focused agencies of governments, business enterprises, research and education bodies - and civil society networks. Different bodies and networks have different resources and capabilities, and different degrees of access to finance, to civil society, public opinion and media, to regulators, and so on. Engagement is valuable for reasons that go beyond enhancing the input of relevant information to the Foresight process, and beyond providing the legitimacy that comes from a wider (if not actually democratic) sampling of perspectives. It means that the participants in the process will have a fuller understanding of the Foresight exercise, and of the issues that it is addressing. This means that they should have increased awareness of important facets of these issues, and thus have greater preparedness to deal with contingencies as they arise. They should also have a better understanding of the perspectives and likely responses of other participants, and thus be more able to explore possible collaboration and cooperation – or sometimes to achieve a better competitive position compared to others. They will, furthermore, be able to act as "carriers" of the messages from the Foresight exercise – they will know more about it, and more about the logic and evidence on which the results and prescriptions are based. Compare the extent of learning achieved from taking part in group discussions and dialogues, with having a report explained to you, to simply reading it on your own.

The orientation to Foresight that has been articulated above was increasingly prominent from the 1990s on. It emerged in the course of applying Foresight to Science, Technology and Innovation

(STI) policy challenges. (Many early Foresight exercises focused on determining priorities for R&D and related funding, for example). Issues of skill and training often emerged in the course of such exercises, but were rarely foregrounded. Much subsequent Foresight has had a wider brief – though STI questions have often loomed large (as befits an epoch of rapid and disruptive technological change). Foresight perspectives have been adopted in fields as disparate as environmental studies, health planning, criminal justice and intellectual property law. However, emerging technologies provide a persistent challenge. Large-scale, fully-fledged Foresight exercises are thus imperative if skills and training agencies are to confront the challenges of technological change – the skills implications of nanotechnology (SKIN) in particular.

The present essay does **not** set out to design such a Foresight process. This would require a substantial scoping study, related to the specific user requirements (e.g.. national governments and international organisations have quite distinct requirements, and these in turn will differ from those of, for example, trade unions and professional associations). It focuses on how innovation studies' perspectives on major technological changes can inform such a SKIN-oriented process. The argument is that innovation studies can be used to pinpoint critical issues for the design and substance of Foresight around SKIN.

1. Emerging Technologies and the Rise of Nanotechnology Wave

What are emerging technologies? The term has itself emerged, along with a host of others – converging, disruptive, radical, revolutionary, and the like are terms used to signify that some new technologies are rather more significant than others. They may signify a substantial change in the way that something is accomplished or a widespread adoption and application of a new way of doing things (Gokhberg et al., 2013). Moreover, the term is used to mark S&T areas whose further development is of high importance due to their expected potential impacts on economy and society.

Use of the term "disruption" generally implies that the structure of industries and markets is seriously perturbed by a new way of doing things. The main accounts of "disruptive innovations" (Christensen 1997, 2006) began with technological change, but subsequently stress that while disruption may be a matter of a challenging new technology (e.g. electric lights displacing gas lamps), it may also be a case of new business models, such as low-cost airlines.

Some other approaches to classifying technological innovations, in contrast, focus on the amount of change involved for the user of the innovation. Freeman (1974 – see also Freeman and Louca, 2002; Freeman and Perez, 1988) was a pioneer in spelling out how and why the significance of innovations in industrial processes varies considerably. Some new process technologies are relatively minor modifications of familiar devices used in specific applications. These usually require little retraining and reorganisation of activities, and they may only reduce product costs or increase quality by a fractional extent. At the other extreme, some new process technologies represent dramatic changes: they can be used to modify the methods of production in many sectors, and are liable to promote considerable rethinking of work organisation and even of the nature of the end-products of user organisations.

Freeman (1974) thus proposed a typology of innovations, which are, in terms of increasing significance:

- **Incremental Innovations.** These occur more or less continuously, including in later stages of the product life- cycle; they usually involve small modifications with only minor implications for training, working practices, organisation; they often derive from inventions and improvements originated by engineers, workers, or user suggestions.
- **Radical Innovations**. These involve more substantial change, which may lead to new training, new organisation of work and organisation practices – one "rule of thumb" for distinguishing radical from incremental innovations is whether new manuals have been written. Radical innovations frequently derive from formal R&D activities, usually on the part of the supplier; they may well involve product innovation as well as changes in production processes and organisational arrangements, and thus they may create new markets or extend old ones - setting off new product cycles, or "dematuring" established products.
- **New Technology Systems**. Here, beyond a specific branch or sector, basic inventions (perhaps the result of R&D in supplier industries that have heretofore had little contact with the users) are forming the basis for reorganising a whole set of production processes. Both radical and incremental innovations based on the new technology emerge, in a range of related sectors. New technology systems are liable to develop over a relatively long period, since they require substantial organisational innovation and the generation of new markets.
- **Technological revolutions**. In this case fundamental basic inventions constitute new "heartland technologies" that can be applied to transform production - and generate new products - across a very wide spectrum of activities, across many sectors of the economy. In effect many new technology systems are developing simultaneously. A long period of diffusion and development is likely as many social, institutional and organisational

> changes are initiated in different areas. The emerging technology (or cluster of technologies) that is at the core of the revolution is liable to itself be the subject of continuous (and quite possibly rapid) development at the same time as applications from earlier versions of the technology are beginning to appear in numerous locations.

It can be difficult to say at an early stage of their development that particular technologies are, or will become the basis for, disruptive innovations. Nuclear power systems work, for example, but have rarely had much impact on the fossil fuel-based energy industries. (France is an exceptional case here, and underlines the point that political factors may play in an important role in determining which technological potentials are realised.) For the purposes of the current essay, we shall consider emerging technologies to be those technologies whose proponents claim, with some supporting evidence, to be potentially the revolutionary technologies of the near future that will enable disruptive innovations to take place across the economy.

Of course, nanotechnology (NT) is one, perhaps the leading, case of an emerging technology at the time of writing. Biotechnologies based on new knowledge of genomics are already finding so many applications that they are hard to describe as emerging, though (like the Information Technology revolution) the biotechnology revolution still has a way to go.

NT draws upon a rapidly evolving area of knowledge related to the improvement of methods of study and control of matter at the molecular level to produce materials, devices and systems with new, not previously achievable technical, functional properties (further on basic definitions and key indicators see OECD, 2009). Along with information and biotechnologies, nanotechnologies are incarnating a new era associated with the increasing role of science and technology and innovation factors in economic development. This becomes possible due to the multiple-use nature of NT applications across a wide range of economic activities that has attracted increasing attention to them from various market participants.

Despite high expectations, backed by very substantial public investment (see, for example, Roco, 2007), current ideas about the potential – and even the actual – economic effects of nanotechnology are still very incomplete. There are a huge number of information sources on nanotechnologies; but there is still relatively little reliable and comparable statistical data on its development. The rapid expansion of R&D in related areas carries not only the expected benefits, measured in millions of dollars (ObservatoryNANO, 2012), but also the potential risks of economic, social, environmental, legal and ethical considerations (Turk et al., 2008). This combination of significant amounts of R&D expenditure with achievements that may be in the longer term perspective, with the need to incorporate a variety of risks, means that governments' have important roles in regulating the creation, transfer and application of NT (Palmberg, 2008). In many countries, such practices have been implemented through the launch of national initiatives, defining the framework conditions for their development. By 2008, the number of large-scaled programs of public support for nanotechnology exceeded 60 (Wang, Shapira, 2011: 571). In turn, this calls for assessment of status and trends in the sphere of NT, formulated in terms of costs, outcomes, and socio-economic impacts, based on a system of reliable statistical indicators. Such assessments and indicators are designed to ensure the identification of boundaries and structure of the new and rapidly evolving area, becoming a cornerstone in the development of regulatory regimes and evidence-based policy frameworks.

This essay will draw in part on Russian experience with mapping and monitoring NT developments. In Russia, the beginning of an ambitious program of NT development and, accordingly, generating statistics of this area, was laid by the President initiative "Development Strategy for Nanotechnology," adopted in 2007. It clearly defines the need for a system of integrated information-analytical support of NT R&D to make effective use of financial and organizational resources to conduct interdisciplinary research and the establishment of competitive domestic market of nanotechnology-enabled products. Continuing the President's initiative, the ongoing "Program of Nanotechnology Development in the Russian Federation until 2015" involves steps towards the construction and use of integrated assessment system based on statistical indicators and carrying out related work on amending the current forms of national statistical reporting to reflect the performance of the NT sector. However, the practice of implementation of existing initiatives and activities of the Russian Corporation of Nanotechnologies (RUSNANO), a support and co-financing projects in the field of nanotechnology, shows different approaches to the understanding of activities related to NT. This again emphasizes the importance of organizing a unified system of concepts and experiences of leading international organizations for standardization and measurement.

Before we plunge into a more detailed discussion of the issues in measuring, assessing and forecasting NT developments, we should consider some basic principles concerning technological change, that have emerged from the body of research that goes by the name of innovation studies. We will need to consider broad patterns of technological change and then go deeper into the nature of emerging technologies.

2. Innovation Studies: Technology Shifts and Economic Growth

Studies of the introduction and diffusion of new technologies demonstrate that major shifts in technology often take considerable time to diffuse (e.g. David, 1991; von Tunzelmann, 1978). Organisations and individuals need to learn about new practices and their potential, new networks and supply chains have to be established, bottlenecks and design flaws have to be ironed out, and so on. It is also clear that successful innovation will typically require "product champions", influential people who will continue to support and promote the innovation even when times are tough.

But there are cases of rapid take-off of particular innovations. Diffusion studies (e.g. Rogers, 1995) indicate that this is most likely to happen when:

- the new products are highly visible so that their features – and especially their benefits - can readily be appraised;
- these benefits of these features are large, especially where compared to costs of acquisition (which should be relatively low;
- the expectations of how difficult it will be to adapt practices and learn to use the innovations effectively are seen as low;
- organisational alignment is relatively good, adjustment and conflict around work systems, jobs and status, communications are seen as being relatively unproblematic.

Often such conditions will only be achieved after a great deal of effort on the part of suppliers. There may then be a dramatic take-off after a long period of disinterest (other than on the part of a few pioneers). Examples are the extremely fast uptake of microelectronics (NC Machine tools, robots, etc. in manufacturing; word processors and PCs in office work) in the 1980s, and of the Web and mobile phones in the 1990s. Interestingly, while some of these new applications of IT had been widely heralded, the success of cellular telephony – and text messaging (SMS) services within this – came as a great surprise to many commentators.

The Web is a good case of a "design paradigm" that established a market – especially once the web browser and search engine services were introduced. Most observers had anticipated a take-off of Internet use once PCs were widely available. Moreover, until the Web burst onto the scene (following the innovation of browsers and search engines) there was little sense that common formats and standards were required. In consequence, much effort was wasted on developing unique and obsolete interfaces when people were seeking to develop new online services. The Internet had been in use for decades, but it took improved PCs and networks, and visibly useful and user-friendly services, to promote widespread uptake. This rapid adoption of the Internet and Web services helped underpin the “dot com bubble” of the end of the 1990s. In terms of establishing a market, it required compatibility with social practices and availability of skills or at least minimising radical challenges. Thus fax was initially preferred to email in part because it could be treated as an extension to secretarial letter-writing while email took off once professionals were themselves used to using PCs to prepare documents and could see the advantages of electronic transfer of information. A critical mass of users may be helpful to establish economies of scale (e.g. costs of equipment and software), network externalities (other users to communicate with), and the conditions for the emergence of competing suppliers (driving down costs) and complementary products (increasing functionality). A successful design paradigm establishes such a critical mass, while adopters may be reluctant to invest in non-standard products.

Discussion of technology development and diffusion of innovations is inevitably associated with the familiar subject of logistic S-curves. Though familiar, the subject is worth revisiting, with the diffusion, product cycle, and industry cycle versions all being relevant to the present essay. Figure 1 presents the classic S-curve. In **diffusion** analysis, the uptake of an innovation is often modelled in these terms, since the diffusion of many innovations follows the basic pattern. A period of slow uptake is succeeded by rapid growth, which in turn is succeeded by slower growth as most potential adopters have acquired the new product. The growth of sales may not mirror the growth in the proportion of the population using the product, because some products, at least, can be acquired repeatedly – automobiles and TV sets, for example, are not only replaced, but many households own more than one. It would be interesting to see how far such a pattern of diffusion applies to current NT-related products, such as, for example, suncreams and cosmetics involving nanoparticles.

S-curve diffusion analyses typically draw attention to the characteristics of early and late adopters. At the individual level, early adopters are typically have higher income, more highly educated, affluent, and linked in to mass media, etc.; at the firm level they are typically larger, in more metropolitan regions, linked to international firms (the classic reference here is Rogers, 1995). If we consider the diffusion of major new technologies which can be applied to numerous ends, we can also consider there to be a pattern of diffusion across sectors, with some being early adopters, some later. For example, early adopters tend to be high-tech sectors, and probably those with closer links to the sectors in which the innovation was first developed and/or applied.

Such S-curves also point to critical uncertainties in forecasting diffusion. For instance, if a take-off is expected, how long will it be before this can be unambiguously identified, and how rapid will it be? On the other end of the curve, where is there likely to be a ceiling? What is the potential population of adopters[3] - and the potential level of incidences of adoption?[4] Even if we are restricted to one application, might there be more of the products in question diffused than there are individuals?[5] Should we treat different applications involving the same basic technology as discrete cases of innovation?)?[6]

Forecasters need to be aware that there are often deviations from the general picture. While S-curves frequently provide rather good fits to empirical data, in practice they are often interrupted by such events as wars and economic downturns. Innovations may substitute one for another, too. A competing technology may displace a given innovation before it has been adopted by all of its potential population – some firms have leapfrogged fax and gone directly to email, for example, while consumer fax never really took off. A famous historical example was the displacement of gas lighting by electric lighting: gas systems could certainly have been extended to many more locations had not electricity networks been introduced.

This brings us to the second context within which S-curves are widely used to describe innovation processes, where the focus moves from adoption of the product to the shaping of the product itself. We will mention the **product life-cycle** in a moment, but first we should note the **industry life-cycle** approach, that was initially developed in the context of discussions of international trade and the changing international division of labour. This approach was used for understanding the ways in which production in certain industries, and of certain products, was shifting across the world. (Vernon, 1966, was a pioneering analysis.) The basic idea here is that industries are liable to "mature" over time. The products they create become more standardised, their processes become routine, and the production technologies that they require becoming cheaper and/or simplified. They are less dependent on a highly-skilled workforce.

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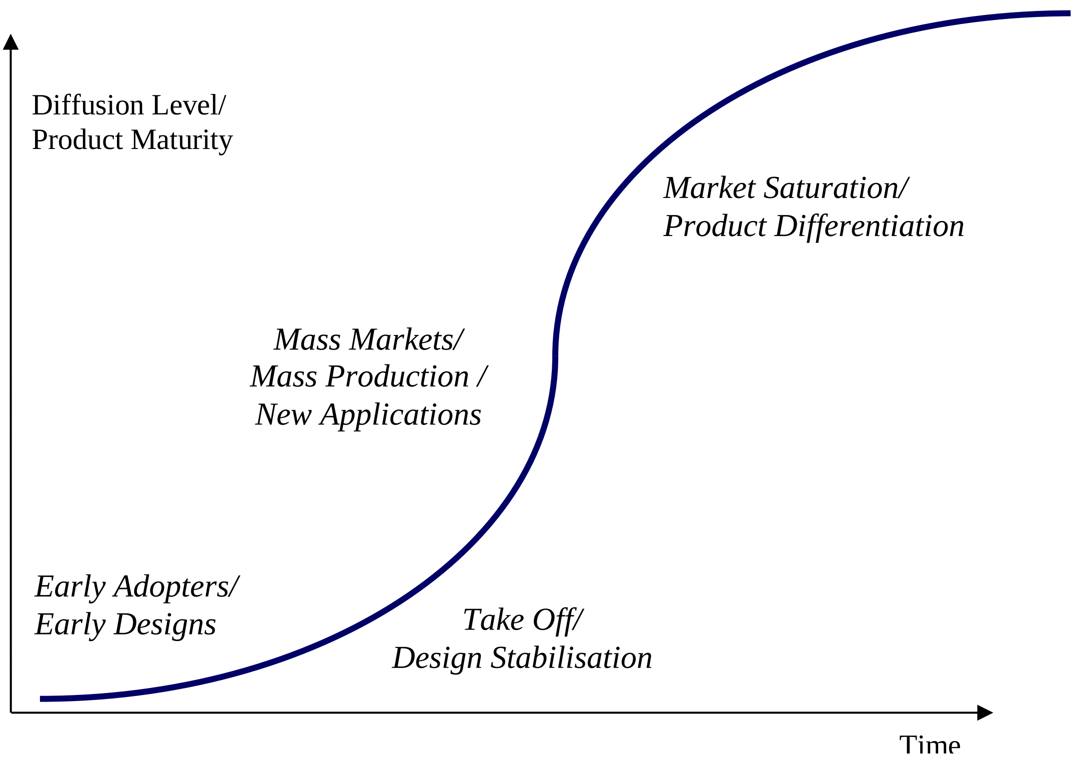
[3] We may find that we have mis-specified the population – among consumers, the estimates may have missed out children, and in the employment data they may miss foreign workers, among firms, the informal sector, and so on.

[4] Often consumers will acquire multiple instances of a new product – especially as it becomes cheaper and more functional. Thus households (and even individuals) often have many radios, several TVs and cars, and so on.

[5] The number of mobile phones in use in some countries exceeds the population of these countries; and it is not surprising that there are more phones used in business than there are firms, nor that there are many more instances of use of common tools than there are of firms in the user sectors.

[6] A slightly different point should also be made. Sometimes users are involuntarily adopting an innovation, because the suppliers simply change the product and withdraw earlier versions. Sometimes this is accompanied by publicity as an effort is made to secure more of the market; sometimes (for example when cheaper ingredients are being used) it may be covert. In the latter case, conventional S-curve accounts may be inapplicable.

Figure 1 The S-curve



Source: synthesis in (Cawson et al., 1995), drawing on many earlier accounts

Novel and less mature industries usually need to be based in technically advanced regions, where they can access high skills, technical support, and innovative equipment and component suppliers (e.g. see Kutsenko, Meissner, 2013). As they mature, however, they can more easily be located in less-advanced countries: transnational corporations may establish offshore production facilities, indigenous firms in developing countries may emerge as low-cost competitors. This approach was used to account for the shift of some established industries out of the more advanced countries – and to recommend that these countries should increasingly specialise in newer high-technology industries. The approach has its critics – how far does it apply to individual products, product classes, firms, industry sectors; how to account for the persistence of many established industries in some advanced countries; how to handle the phenomenon of "dematuration" and shifts away from Fordist production systems? – but again it points to some underlying dynamics of successful product (i.e. technology-enabled) innovation.

Empirical support for the approach is less conclusive than for S-curves in diffusion analysis. In part, this is because many industries display continuing change and innovation, such that important shares of activity can be retained in the original high-tech countries. "Dematuration" may take place, with technological and organisational innovation undermining the comparative advantages of low wage economies. For instance, new process technology may make labour costs less relevant, and new skills may be required in the labour force. Additionally, closeness to markets, and flexibility of response to more volatile markets, may be important; some sectors may not migrate because of political or corporate strategy. The developing countries themselves may become pioneers in the sector, rather than imitators of established technology – and there has been little sign that sectors are moving around the world to increasingly less developed countries. Finally, it is striking how many industrial activities have been offshored, with many forms contracting out specific assembly and service activities overseas. Some analysts have argued that intensified international division of labour would mean that latecomers would be restricted to less knowledge-intensive components of value chains, and be unable to acquire capabilities to play much of an autonomous role in industries because they are only experienced in working on small fragments of extended production processes.

Still, the basic ideas of the industry cycle approach do have continuing relevance. There are, and are likely to continue to be, shifts in the sites of production shifts and changes in the international division of labour. The dynamics of new technologies requires examining more than one country in isolation in terms of the location of production processes as well as the pace of adoption in different regions. Latecomers can take important roles in industrial production – and in some cases important new products can emerge from them. Pioneers cannot assume that their own products will continue to dominate in other regions of the world.

The **product life cycle** approach introduces further points that are particularly relevant to considering the dynamics of new technologies. This approach draws on both the diffusion and the industry cycle models, together with the accumulated results of many innovation studies. (see Utterback, 1996 for the Abernathy-Utterback model). The focus here is not so much on how the market or sector evolves, but on the nature of the innovation itself.

Put very schematically, the product life cycle approach suggests that early versions of innovations are typically, even is technologically sophisticated, very basic and rudimentary as compared to their later incarnations. The early versions of the innovation appeal to relatively few users, not just because the markets are underdeveloped. Additional factors include the lack of widespread knowledge of their current and potential capabilities on the user side, and the lack of knowledge on the supplier side of just what capabilities will be valued and how they may be used. This underpins the stress placed by many innovation researchers and practitioners on good communication links between users and producers, which informed the development of the "systems of innovation" approach. It also leads to considering that in the early stage of product development and diffusion there may be poor linkages between the innovators and many potential users – and types of user (i.e. applications of some sorts may be quite well established, while others are much less mature or even yet to be created). More generally, the organisation of upstream supply chains and downstream systems for distribution and training, are liable to be rudimentary. A successful product life cycle will see these features changing as product development and diffusion coevolve. At the early stage of development, complementary goods and services are not available, or not widely available. The key products themselves are liable to be expensive (and often unwieldy and/or unreliable), as compared to later versions of similar products. They early versions of products are liable to require considerable technical skills for their production and use, while these may become routine practice in later stages. Skills that were rare to begin with, too, may have become much more commonplace as training agencies and employees themselves see the need for them.

However, if the products do gain a foothold, then awareness of them increases, investment in them grows, experience as to how to apply them accumulates, and their markets expand. This is in line with the diffusion account, but crucially we here see that the innovation itself is changing. The product is redesigned so that it becomes more robust, easier to use, capable of more efficient production. The early suppliers, who have demonstrated the potential for a substantial new market, are joined by new entrants, who may offer new designs for the innovation. Often there is a competition between different types of design, with one becoming the dominant "design paradigm" to which others should conform. If the early suppliers are innovative small firms, large firms are liable to substantially change the nature of the competition in the market (perhaps acquiring the small firms in the process); with superior marketing capacities, the large firms may accelerate the diffusion process and fasten the development of a dominant design. Then, as the market grows, the focus of innovation typically moving away from basic product/design innovation, toward improving product quality, and then to process innovation enabling larger-scale, cheaper production. This resembles the industry cycle analysis. The product becomes cheaper to use, with complementary goods and services, higher functionality and adaptability, less requirement for high skills in its use. It can be acquired more readily, with replacement, repair and perhaps second-hand markets. One version of this account describes the product cycle as involving a shift from technology-push to demand-pull, though this is somewhat oversimplified. However, what the product cycle approach does draw attention to is a pair of learning processes. On the one hand, successful innovations themselves evolve through an extended development process once they are on the market (not only when they are precommercial prototypes in R&D laboratories), as suppliers learn what users require. On the other hand, users learn about the product and about how to use it effectively. The latter part of the user learning process may be very protracted – for example, it is believed that the “productivity paradox” of new IT was only resolved once users had learned how to apply their large IT investments effectively (Joergenson et al., 2008). There is a related message here: since users play an important role in shaping innovations, it is unwise to assume that inventors and developers of innovative products have a clear view of how these products will be used.

This leads us beyond the literature on S-curves, towards those on organisational learning, on technological configuration, and on “reinvention”. Adopters and creators of complementary innovations may effectively modify the innovation – for example, by finding ways of using it, and areas of application, which were not anticipated by the inventor or even the by a supplier years after the first introduction of the new product. While by the early 1980s PC manufacturers were already becoming aware that consumer markets were developing for computers on which to play videogames, for example (which would have surprised computer pioneers!), few would have anticipated the emergence of large scale music and video downloads, of Web 2.0 social networking sites, and so on.

These approaches also imply that the social and technological networks of which the economy is comprised themselves evolve during the innovation process, as changing linkages between producers and users of innovations are established, as new intermediaries (including regulatory and training organisations) arise and traditional ones modify their roles, and so on. The social networks that are required for successful diffusion of an innovation may themselves take time to develop – especially if we are looking at a region where there are not already intensive innovation clusters operating. The networks may be stimulated or impeded by policy action, but efforts to create them rapidly from scratch often fail.

It has been necessary to introduce the various themes presented above in order to provide a reasonably firm ground in innovation analysis for the discussion of nanotechnology. It would be too easy otherwise to be carried away by the hyperbole that has accompanied the recognition of the potentials of doing things at nano-scales.

The common ground between the various perspectives examined is the anticipation of continuing change and growing capabilities. The revolutionary technologies of the past were once emerging technologies – but a large number of less significant innovations were also, of course, once emerging. In this paper we will be taking emerging technologies (ET) to be those where there is a plausible case as to their underlying new knowledge and innovations having major and widespread implications – having applications across many sectors of the economy, for example.

Whether what we will witness will be a technological revolution, or a loosely connected series of radical changes in technology system[7] across a number of industries (manufacturing, health, etc.), there are still liable to be substantial implications for employment, skills, industrial structures, and the like. Experience with earlier major changes in technology can be a useful guide to thinking about these implications of NT. In developing such “historical analogies” (Bell, 1964) we should always be mindful that both specificities of technologies, and contextual changes such as globalisation and economic competition, economic up- and downturns, and even wars and other crises (environmental, health, security, for example), may reduce the scope for generalising from past experience. Such factors may slow down the pace of change, or speed up particular technological developments. They are liable to create markets (e.g. public procurement, more or less luxury products), and thus to focus innovative efforts.

3. Nanotechnology as Revolutionary Technology

3.1. Which Nanotechnologies?

Many commentators[8] hail nanotechnology (NT) as the next technological revolution (one of the latest see Roco, 2013). In some accounts, this will be the successor to the well-established Information Technology (IT) revolution and the still-accelerating biotechnology (BT) revolution. Other commentators, in contrast, are sceptical of many particular claims as to future NT potentials – they argue that nano-robots and atom-by-atom assembly are at best long-distant prospects (e.g. see Smalley, 2001). Therefore, the major investments in nanotechnology R&D programmes in the early years of this century have failed to bear as much fruit as anticipated, to create the huge markets that were forecast. Nevertheless, even sceptics are liable to be impressed by the wide range of emerging developments and applications that go under the NT label.

This leads into another line of criticism: that NT developments are too multifarious to be classified together as a coherent body of knowledge development. Sceptics point out that many

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[7] The concept of system innovation was initially used by Freeman and his colleagues to discuss changes that affect whole sectors, but have limited impact on many other parts of the economy. It is now also being applied by researchers such as Geels (2005) to focus on the sorts of large-scale change required in major sociotechnical systems in order to effect shifts to sustainability.

[8] Classic work that stimulated (and even provoked) further discussions on nanotechnology development and its possible impacts on economy and society is (Drexler, 1986).

activities have been reclassified as NT for reasons of attracting funding (and might move to other terminology once fashions change). Currently, there is no internationally accepted definition of NT that can be applied to more or less accurate description and observation of this area in terms of economic and social relations. A key reason for this appears in a complex nature of NT itself – it is a rapidly evolving but weakly structured S&T area (Youtie et al., 2008).

NT involves control and restructuring of matter at the nanoscale lavel – usually taken to mean less than 100 nanometres. Simply being able to examine or measure nano-scale phenomena is not itself NT, but this says little about what is controlled, how, and in what ways, with what effect, for what purposes. Advanced materials are rather different from nano-precision engineering, and different again from nano-level etching of silicon chips and work with biological molecules.

The case for NT as distinctive, relatively coherent, and potentially revolutionary is intriguing. The argument is that major increases in our transformative capacity can be – and in some cases already have been – realised by working at nano-scales. For millennia human beings have been producing and applying "new" materials, and many materials that are only familiar in recent decades – for example plastics – actually have a relatively long history. There are extremely intriguing and completely novel (or unknown) substances that have recently been developed – for example, the fullerenes, carbon nanotubes, graphene and metcars. NT means new approaches to Advanced Materials (AM) – not just a particular class of new material, nor even application of a particular technique or set of instruments to producing materials. NT knowledge, as applied in economic activities at present, is largely a matter of developing and adopting a range of new processes to the production, shaping, and configuration of materials. In other words, NT allows utilising effectively the properties of AM or of familiar materials processed in new ways (e.g. "chips" with circuitry engraved upon them) can be defined at very great detail, at nano- and indeed atomic or molecular levels.[9]

Mike Roco (2011) of the US National Nanotechnology Initiative argues that there will be four generations of NT development, as depicted in Figure 2. It is already apparent that he was far too optimistic (if this is the right word) about the pace of development, but the posited trajectory of change constitutes a compelling vision – and the conceptualisation of distinct types or stages of NT development is one we may be able to build upon. His set of generations is:

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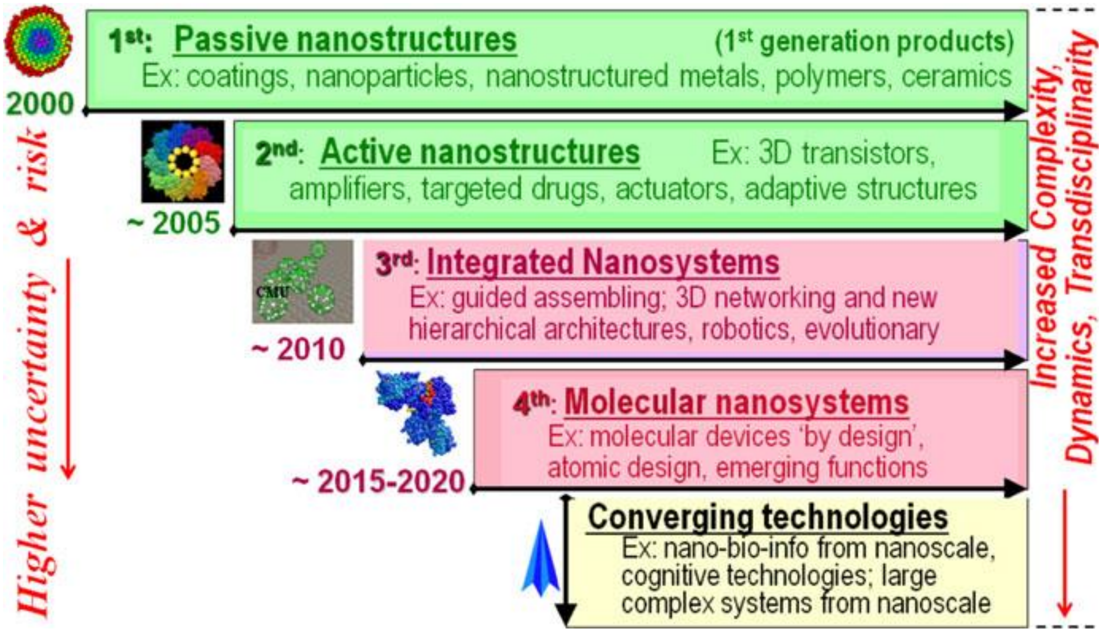
[9] A very helpful discussion of this point in the context of AM was provided over two decades ago by (Cohend et al., 1991).

- First generation, turn of the century – **“passive nanostructures”** and is typically used to tailor macroscale properties and functions. These are materials designed to perform one task, whose specific behaviour is stable in time. Examples include: nanostructured coatings, dispersion of nanoparticles, and bulk materials - nanostructured metals, polymers, and ceramics.
- A second phase, which Roco saw as beginning in the early years of this century – **“active nanostructures”** for producing mechanical, electronic, magnetic, photonic, biological, and other effects. These are typically integrated into microscale devices and systems. Examples include new transistors, components of nanoelectronics beyond CMOS, amplifiers, targeted drugs and chemicals, actuators, artificial “muscles”, and adaptive structures. It is arguable how much progress has been achieved in this sort of NT to date, so the timings for all subsequent phases can be expected to slip considerably!
- A third generation – **“integrated nanosystems”** with three-dimensional networking and new hierarchical molecular architectures, constructed with thousands of interacting components, by means of various syntheses and assembling techniques such as bio-assembling, robotics with emerging behaviour, and evolutionary approaches. A key challenge associated with construction of such systems is enabling networking to take place at the nanoscale. Roco mentions some research areas that will underpin this: heterogeneous nanostructures and supramolecular system engineering. This includes directed multiscale self assembling, artificial tissues and sensorial systems, quantum interactions within nanoscale systems, processing of information using photons or electron spin, and assemblies of nanoscale electromechanical systems (NEMS).
- Fourth generation – **“molecular nanosystems”**. These are seen as integrated nanosystems, with hierarchical systems within systems (functioning much like the cells of complex organisms). Each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices: their engineered structures and architectures will permit fundamentally new functions. This will lead to nanoscale machines, nanosystem biology for healthcare, and new human-machine interfaces at the tissue and nervous system levels, for example.

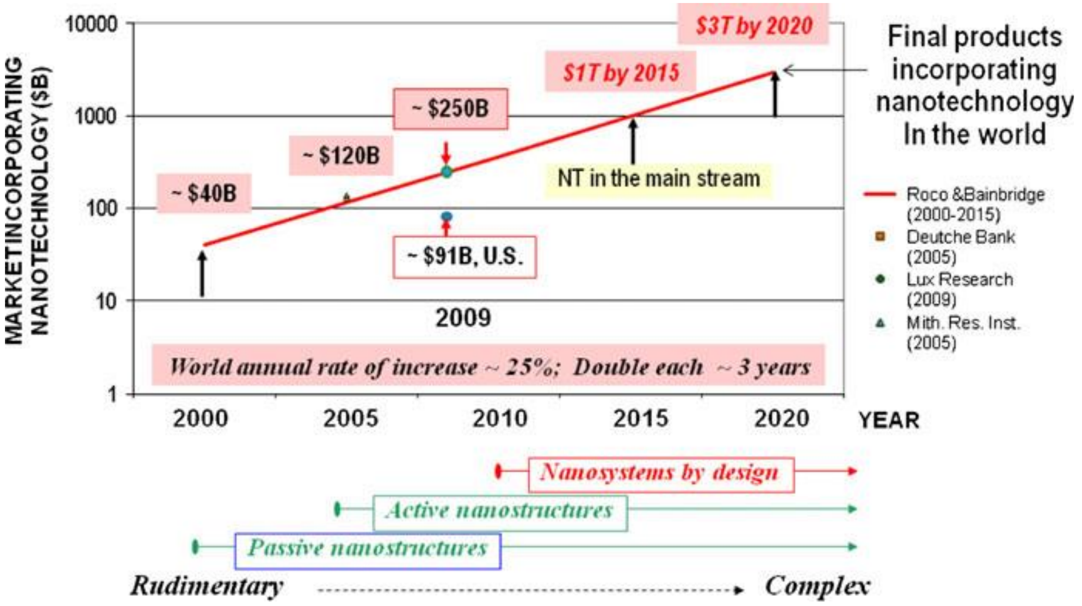
Figure 2. M. Roco's forecast of generations of Nanotechnology



Source: Roco (2011).

After 2020 nanotechnology is expected to develop closely to other emerging technologies, creating new convergent science and engineering domains as well as manufacturing paradigm. The new challenge is related to combine use of nanoscale laws, biological principles, information technology, and system integration in nanoscale object design and building. After 2020, according to Roco's vision one may expect various divergent trends as a function of system architectures. Several possible divergent trends are system architectures based on guided molecular and macromolecular assembling, robotics, biomimetics, and evolutionary approaches. Figure 3 also displays Roco's estimates of the developments of NT markets. We may wish to add a decade to the forecasts insofar as they feature the different generations!

Figure 3 Forecast of Market size of Nanotechnology



Source: Roco (2011)

The timing is evidently rather different from Roco's expectations, which display the sort of optimism characteristic of the early stages of technological revolutions. Perhaps it is an advantage that we still have time to reflect on the implications of the changes that are underway. Roco's proposed trajectory of change seems quite plausible, though, reflecting as it does increasing complexity of operations and outcomes as our capacity to work at the nanoscale grows.

3.2. Searching for Stylised Facts – Towards a Statistical Framing of Nanotechnology

While NT is surrounded by a high level of expectations related to their possible application in various fields and future market growth, there is little knowledge about its actual development and use. Information on nanotechnology R&D growth, adoption and dissemination of its results in the different types of economic activities is fragmented and nearly compatible. Shortage of data, caused considerably by lacking technical standards and regulatory frameworks for NT and need for elaboration of a common language for describing and analysis of key aspects of its development in socio-economic terms. Therefore, there is a strong interest for statistical framing of economic activities related to NT growth.

Since the introduction of the first S&T indicators in 1920s, the role of statistics significantly changed from simple registration of facts to justification national political programs and frameworks aimed at support of R&D activities (further see Godin 2003 and 2013). Nowadays autonomy of statistical discourse is supported by work of international advisory organisations such as OECD and United Nations, which do a lot for harmonization of approaches to statistical measurement of STI and popularization of statistics among a variety of users. Putting aside further critical discussions on the performativity of statistical and even wider – economic knowledge, we agree that elaboration of statistical definitions and classifications allows operationalization of abstract theoretical concepts and development of indicators for measuring emerging phenomena. Among the examples is well-established approach for statistical studies of innovation activities (OECD/ Eurostat 2005) as well as relatively new guidelines for statistical measuring of ICT and biotechnology (see OECD 2009, 2011). Nanotechnology is a forthcoming area for statistical reflection; therefore, national approaches are of great interest.

Russia has, as noted, taken NT to be a strategic technology requiring substantial R&D support. Accordingly, this country has seen considerable effort devoted to developing frameworks for statistical assessment of the area. Work on this was discussed in a series of expert interviews and focus groups with participation of RUSNANO S&T Advisory Board, members of Scientific Coordination Council for Federal Program ”Research and development on priority areas of scientific-technological complex of Russia for 2007-2012”, the editorial board of the journal “Nanotechnologies in Russia”, participants of the First (2008) and Second (2009) International Forum on Nanotechnology, and elsewhere. One results was consensus around a definition of NT:

> *Nanotechnologies – a set of methods and techniques, related to analysis & control of elemental composition of the matter and processes at the nanoscale level (100 nm or less at least by one or several dimensions) and providing new properties of the matter to create improved materials, devices or systems which utilize those new properties.*

The RUSNANO advisory board in September 2009 accepted this as a working definition as corresponding to ISO definition and far taking into account the complex scientific and technological nature of this phenomenon, points to a specific dimension and control of basic processes, emphasizing their decisive influence on the properties of the products produced and the relation to market innovation. The idea is that the definition can be used for the purposes of determining requirements for scientific and technical expertise, and for formulation of criteria for the selection and evaluation of selected projects related to nanotechnology, as well as for the organization of statistical observation in this area.

On the last point, it should be noted that systematic research around emerging technology requires general definition to be complemented by a list-based definition summarising a set of characteristics of the phenomenon under observation that could be used as classification basis. This allows us to more clearly identify the subject of the survey, which in turn improves the quality of completing survey questionnaires and statistical reporting. The Russian work has involved specifying seven major areas of NT, providing basis for their draft classification:

1) nanomaterials;
2) nanoelectronics;
3) nanophotonics;
4) nanobiotechnology;
5) nanomedicine;
6) methods and tools for the research and certification of nanomaterials and nanodevices;
7) technologies and specialized equipment for experimental and industrial production of nanomaterials and nanodevices (further see Alfimov el al. 2010 or Gokhberg et al., 2013).

Another problem is identification of nanotechnology-enabled products (goods and services). The category in both international and domestic practice has various interpretations, ranging from narrow, whereby the corresponding output of NT is accounted for only nanomaterials and nanodevices, to the wider one in which any use of NT in processing is accepted as an input to a final product. The basis of Russian proposed approach, which will be seen to resemble Roco’s view in certain respects, involves grouping goods and services related to NT, into several types depending on their input to the final product (based on Gokhberg et al. 2013: 375):

A. Elementary nanoproducts.
B. Conventional products (goods) containing nanocomponents.
C. Goods and services based on technological processes using nanotyechnology.
D. Tools & equipment for nanotechnology.

To elaborate on these, (A) *elementary nanoproducts* refer to artificially created NT components further being used within other categories of products. Thus the goods in question contain nanoscale structural elements (about 1-100 nm at least in one dimension) – this is in order to give them new functional and performance properties. Nanoproducts include two major subgroups: nanomaterials and nanodevices. *Nanomaterials* represent bulk materials and films (intermediates), the macroscopic properties are determined by chemical composition, structure, size and / or relative position of nanoscale structures (ensembles of atoms or molecules, which are at least in one dimension have a size less than 100 nm and structurally indistinguishable from the surroundings). For example, nanocrystals and nanoparticles, quantum dots, nanotubes and nanowires, two-dimensional nano-objects with the characteristic thickness of the order of molecular dimensions, multi-layered and multi nanostructure and the grid, etc. *Nanodevices* are mechanisms designed or constructively finished part of an artificial object of nanoscale level (approx. 1-100 nm), which has some functional purpose. For example, the membrane with nanoscale diameter of crossing channels; single-electron transistor, etc. By the same subgroup are elements of the electronic database of devices with nano-scale (including spintronic devices based on magnetic and nonmagnetic heterostructures, etc.).

(B) *Conventional goods containing nanocomponents* are those containing elementary nanoproducts in their composition so as to substantially affect their functional characteristics and consumer characteristics. The distinguishing feature of such products is the use of special NTs and equipment designed to integrate into the nanoproducts products as components, so that the latter become its integral part (not mechanically assembled). Examples include high-brightness light-emitting diodes (LEDs), solar cells with high efficiency based on nanoelements; high capacity batteries with nanoparticles; metal-cutting tools with nanodiamond coatings, surgical instruments with an antibacterial nanocoatings; pharmaceutical products with active nanoparticles used in particular for targeted drug delivery, etc.

(C) *Goods and services based on technological processes using nanotechnology* are those involving the use of NT as a part of the overall process that contributes to a significant improvement in their performance, but contain no elementary nanoproducts as an integral part. Examples of such products can be highly purified materials, liquids or gases that are produced using nanomembranes as filters or nanocatalysts (e.g. used in oil processing). This category may also include services produced using nanotechnology, requiring special conditions, methods or equipment (services for medical diagnosis based on intrascopic research / visualization using nanomaterials and nanostructures, etc.).

(4) *Tools and equipment for nanotechnology* is a specific category that brings together the equipment require to perform various operations on the atomic and molecular levels in order to obtain, modify, produce, measure and control the properties of nanoproducts. For example, the atomic-force microscope, equipment for epitaxial growth, chemical-processing equipment to make textiles antimicrobial or conductive properties, etc.

These proposed definitions are intended to answer the key challenges of nanotechnology, setting boundaries and composition of this loosely structured interdisciplinary field (for further use of these definitions and classifications for statistical measurement of nanotechnology see Gokhberg et al. 2011). As already mentioned, they focus on the distinctive features of nanotechnology as a scientific research, technological and industrial spheres. We shall consider the application of these categories in a later section of this essay.

3.3. A Heartland Technology?

At this moment, it is difficult to determine a fundamental new set of instruments for working at the nanolevel. Indeed, at present there does not seem to be one “heartland” NT, in the way that microelectronics has been for information technology, or gene sequencing/manipulation for biotechnology. It is possible that one may emerge, that one of the existing techniques will prove to be the basis for numerous rapid developments. However, the diversity of approaches to NT - from microelectronics, materials science, biotechnology, pharmacology, etc. – may make this unlikely. Even the IT example is one where, despite microelectronics being an obvious case of a heartland technology, there are numerous related technologies, some complementary (e.g. software) and some more independent (e.g. optronics and photonics). There is limited conceptual and empirical analysis to tell us how “tight” the cluster of core underpinning technologies in a technological revolution needs to be. Ways of understanding the formation of tighter links between different lines of work represents a fascinating area for further research.

In any case, nano-transformation is a set of technologies with extremely wide applicability. For example, take the AM case, where there have been efforts to examine developments for several decades. Barker[10] indicates the potentially great pervasiveness of new materials technology by noting that the materials sectors of industrial economies may well account for 5-10% of output, and that materials can account for as much as 60% of the cost of manufactures. AM currently constitute a small proportion of the total materials markets - and thus the AM revolution, if such a thing exists, has a long way to go. But their role in many strategic applications (aerospace, etc.) is already substantial. Barker identifies a series of characteristics that distinguish new from traditional materials technology: these are summarised in Table 1, and are clearly of such importance to modern industry as to require close attention by producers and users of materials of many kinds. The new properties that AM possess may well create opportunities for new products and processes.

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[10] Barker (1990)

3.4. Innovation and Diffusion

The usual S-curve of diffusion was originally introduced to describe the pattern of uptake of a particular artefact or process across individuals, regions, or enterprises. Using it to describe patterns of uptake across sectors is an obvious step, and one that is useful for thinking about skills and employment implications of a new technology. A problem with SKIN, however, is that NT is now just one technology, and is potentially something that can be embodied in many types of application and artefact. It will be more difficult to assess (and predict) diffusion trends for NT than it was for, say, microelectronics – where surveys did enquire into the share of products and processes employing microprocessors, for example, or produced or controlled by robotics.

The listing of applications of NT in section 4.2 can fairly readily be translated into sectoral areas of application. An earlier effort to fit a prospective chronology to NT applications was made in a study for Texas technical colleges by Vanston and Elliot (2003). Their overview is presented in Table 2. The trends in this forecast seem to refer, at least to a large extent, to end-uses. Thus, electronics does not appear as an application area in its own right - though nanoscale engineering is already a reality in this sector. Notable is the expected shift from high-tech military/aerospace applications to those focusing on social concerns such as health and nutrition.

More elaborate forecasting of skill requirements will need to have more detailed and better-grounded estimates of NT uptake in various application areas and sectors. Probably the best step would be to identify a key set of NT applications and then seek to estimate the extent to which they will be taken up, at what speeds, in different sectors, countries, types of firm, etc.

In the absence of solid data, or even of expert judgements that allow for sufficiently detailed analysis, all we can do at this point is to present a schematic depiction of the sorts of development that are liable to occur, if NT proves to be a generic technology, or set of technologies, with applications across many domains. This future seems entirely plausible, given the striking wealth of applications that is already emerging from first generation NT. Thus, Figure 3 outlines the likely emergence of multiple diffusion curves, as new nano-tools are developed – applications of various kinds, adopted across wider or narrower sets of user sectors. It does not attempt to fit exact time lines or specify the lead and lagging user sectors – this is a matter for detailed examination by experts (though it is possible to make some generalisations about the types of firm and sector that are liable to be lead users).

We are always liable to be surprised as products find applications well away from those considered by the pioneering inventors and innovators. We are also likely to find that the take-off of some diffusion curves is slower than anticipated, as regulatory, technical or skills problems kick in. This is probably one reason for many forecasts of rapid generational change already appearing premature (see NIA, 2007, for a striking and more realistic view of such a change.)

Table 1. Characteristics of New Materials Technology[11]

- **Information Content** R&D, Processing and design expertise are much higher proportion of total costs, energy and raw materials lower.
- **Complexity** Greater control of materials microstructure, so AM often constituted by a series of phases yielding a desired microstructure with specific properties. Requires multidisciplinary knowledge inputs.
- **Integration of Function** Packing of more performance characteristics into smaller areas and volumes, reduced steps in manufacturing process.
- **Added Value** High unit prices related to information content and level of processing required.
- **Variety** Broad and diverse range of materials, reflecting variety of manufacturing methods and raw material inputs, and amount of scientific and engineering knowledge, now available; so scope for more customisation to user requirements.
- **Market Size** Already having impact on nearly all sectors of manufacturing industry, especially high-tech sectors; likely to have multiplier effect across whole economy.
- **Market Growth** Whereas many traditional materials have mature or saturated markets, AM display rapid growth.
- **Life Cycle** Apparently short, reflecting increased competition among continually evolving materials, and shorter life cycles of products in which used.

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[11] Based on (Barker 1990) op cit.

Table 2. Vanston and Elliot’s Forecast of Commercial Realisation of NT

Short-term (0-3 years)	**Mid-term (3-5 years)**	**Long-term (5+ years)**
Modest Commercial Opportunity		
Instrumentation, tools and computer simulation	Instrumentation, tools	Instrumentation, tools
Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)	Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)	Nanomaterials (metal and ceramic nanopowders, fullerenes, carbon nanotubes)
Important Commercial Opportunity		
-	Life sciences (diagnostics)	Life sciences (diagnostics, screening and tagging technologies)
-	Electronics/IT/optical devices	“Smart” nanomaterials
-	Computer simulation	-
Large Commercial Opportunity		
-	Life sciences (drug delivery)	Life sciences (drug delivery, design and development)
-	Electronics/IT (data storage, microprocessors)	Electronics/IT/optical devices (data storage, memory, optical devices, molecular and quantum computing) NEMS (nanoelectromechanical systems)

Source: based on Vanston, J and L Elliot (2003)

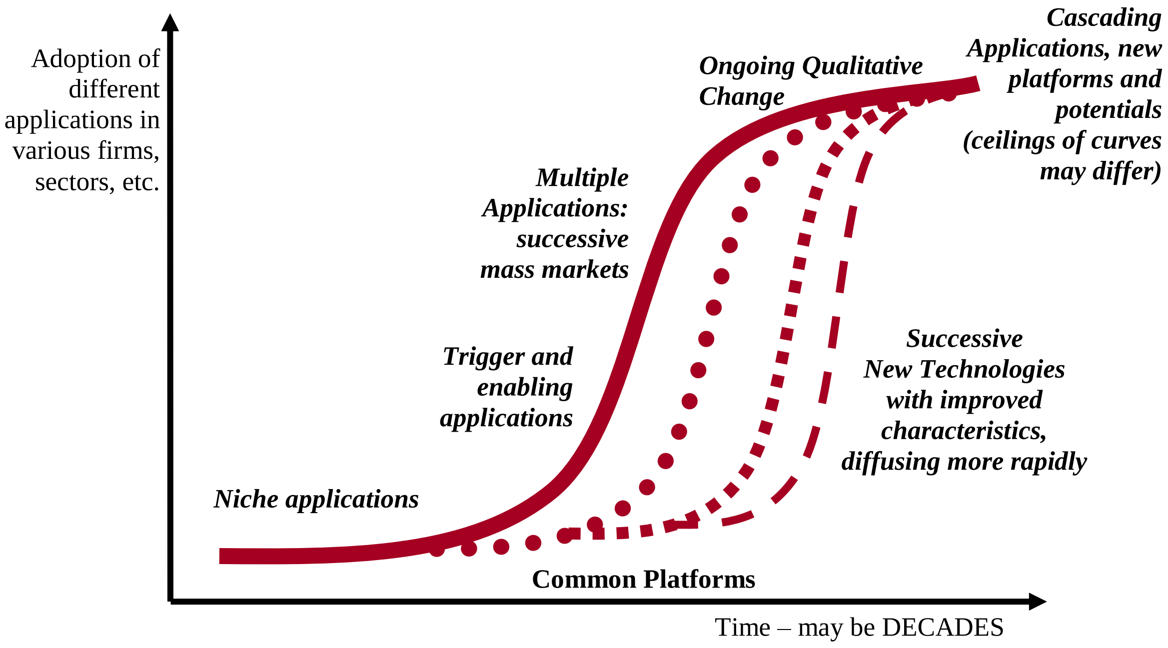
4. Innovation and the Demand for Skills

4.1. Nano-skills?

What do we know about the skill requirements associated with technological change? Clearly, the picture will vary across the different sorts of innovation discussed earlier, so let us focus on major technological changes, affecting many sectors and processes, such as NT is believed to be.

The frameworks set out earlier give us some basic perspectives on how the nature of key technologies typically changes (for instance, toward more standard and usable designs) as the market develops (typically an S-curve of diffusion and a proliferation of applications). These frameworks do not tell us directly about the speed of development in any given area – though we should certainly beware the trajectory of hype! – but they do provide some implications for skills and related institutional issues. We could for example, anticipate a long-term growth (and for a long period accelerating growth) in the requirements for specialist knowledge of the fundamentals of the new technology – in R&D and in emerging applications.

Figure 3 Diffusion Curve of new Core Technologies



Accompanying this, at first with some lag but ultimately outpacing it by many times, will be requirements for skills in the applications of the new technologies, fusing domain-related skills with good understanding of the technology. With another lag, many more workers will be affected in the sense that they will need less specialised knowledge in the technology, though possibly more practical experience will be required about use of the technology in specific circumstances. Typically, we would anticipate the formation of new professional classifications, qualifications, accreditation, and associations and networks over this period; the reconfiguration of training courses and possible some new institutions.

This might be a process unfolding over a few decades, or over many. Predicting the actual pace of NT advance is bound to be difficult. Some recent commentators are anticipating major market take-off in the next few years, for example. Despite the current economic gloom, BCC group (McWilliams, 2012) estimates the global market for nanotechnology was valued at nearly \$20.1 billion in 2011 and and \$20.7 billion in 2012. Total sales are expected to reach \$48.9 billion in 2017 after increasing at a five-year compound annual growth rate (CAGR) of 18.7%. Nanomaterials are expected to have sales in 2017 worth \$37.3 billion (a CAGR of 18.6%) while nanotools should total nearly \$11.4 billion (a CAGR of 19.1%). The global nanomedicine market reached by BCC estimations \$43.2 billion in 2010 and \$50.1 billion in 2011(Highsmith, 2012). The market is expected to grow to \$96.9 billion by 2016 (a CAGR of 14.1% between years 2011 and 2016). Such estimates run into all sorts of definitional problems – are we talking about nanomaterials, systems or things that happen to have been themselves shaped by NT devices? It is striking that after some years where the hype bubble around NT seemed to have burst, it is once again being promoted enthusiastically in various media outlets.

When it comes to discussing SKIN, the situation is somewhat less clear. Some NT proponents are happy enough to stress the potential for job creation. Thus Roco (2007), citing input from industry and academic experts, projected that \$1 trillion in products incorporating nanotechnology and about 2 million jobs worldwide will be influenced by nanotechnology by 2015. This now seems to be another very optimistic estimate. Extrapolating from information technology, where for every worker another 2.5 jobs are created in related areas, nanotechnology was seen as having the potential to create 7 million jobs overall by 2015 in the global market. Indeed, the first generation of nanostructured metals, polymers, and ceramics have already entered the commercial marketplace. Nevertheless, few studies examine more specific skill requirements, especially if we are looking for studies involving substantial research into occupational trends, job announcements, or even industry opinion.[12] Only a couple of such studies have been located while preparing this paper.

One of these we have already mentioned, the Vanston and Elliot (2003) study, which was prepared to inform technical colleges. They stress the uncertainties of NT development, though much of the report considers forecasts that are in general rather optimistic. Because of the uncertainties, basic skills that could be applied in various related fields are emphasised. Colleges were recommended to prepare programmes (in a coordinated way) but not expect to deliver them until demand becomes more clear – which could be the case very rapidly, once take-off is achieved. As already mentioned, the development of commercial applications across various fields are liable to follow a sequence, as (speculatively) depicted in Figure 3. Thus it is

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[12] Roco (2007) noted that "*Small Times* reported 1,455 U.S. nanotechnology companies in March 2005 with roughly half being small businesses, and 23,000 new jobs were created in small start-up 'nano' companies".

possible to speculate about some patterns of emerging SKIN. The area with most graduate employment opportunities in the near future is **nanomaterials**: technicians' jobs include production supervision, quality control, equipment calibration and maintenance, user education, responding to customer requests. One area that is strategically important but may involve relatively few (very high skill) jobs is **instrumentation, tools and computer simulation**. Longer term prospects are bright in **electronic, optical and information applications**, though limited immediate employment will be created: skills may be analogous to those in computers and microelectronics. **Life science** will require higher level skills than those of technicians, and this may be a bottleneck; NT may impact health professions in general; NT applications in environmental areas will require data processing, equipment operation and repair, and administrative positions. This is a promising approach – SKIN analysis will be much enhanced by reliable appraisal of the sectoral diffusion of NT – though in practice the areas examined seem fairly restricted.

Another very interesting study could well do with an update, and it is indeed surprising just how little examination of these issues there has been. Hendry (1999) used interviews and literature reviews to explore emerging and potential skill needs in three new technology industries – optoelectronics, biotechnology, and advanced materials in the UK. Note that the focus is on the supply-side, not using industries. Advanced materials (AM) is the closest to our field of NT, but since it does not specifically focus on the nano-level, a range of other materials activities are involved (and of course, non-materials focused NT is not examined). Advanced materials were defined as polymers, ceramics, and high-performance metals, and composites and laminates of these. The materials area is well-established in the UK, with, for example, an Institute of Materials – optoelectronics on the other hand was highly fragmented. Hendry noted that the take-up of AM was slower than expected, with low-cost high-value products dominating, mainly produced by SMEs as larger firms had withdrawn from the area at the time of writing. Fairly rapid growth was largely being driven by demand from aerospace and automotive industries.

Hendry (1999: 6) noted three key sets of AM skills:

(i) fundamental understanding of the (specific) materials concerned, with skills in synthesis, design, processing, and fabrication;

(ii) supporting infrastructure (generic) technologies such as ultra-precise measurement and testing techniques, modelling and simulation;

(iii) project management skills and appropriate organisation to carry out concurrent engineering, in which the design of a product is done in close conjunction with the design of the manufacturing process, and customers and suppliers are brought into the design process early on, in order to meet ever-decreasing product development cycles.

Studies of skill requirements for materials engineers had stressed the uncertainty involved in developing AM applications. This uncertainty calls for close collaboration with supplier firms, the research infrastructure, and customers, underpinning the need for “soft skills”. Soft skills are described by Hendry as encompassing: creativity, problem solving, proactivity, communication skills, business awareness, and the ability to use and integrate other disciplines. The variety of evolving applications calls for this latter, interdisciplinary or interprofessional ability. In the IT world we are increasingly hearing discussion of the “T-shaped” individual, who combines deep specialist knowledge of one area with awareness of the terminology, principles, and issues in other areas of business and/or technology. A similar appraisal emerges here. Hendry quotes Kaounides (1995) as describing materials science as a

> *“multi-disciplinary science requiring inputs from solid-state physics, chemistry, metallurgy, ceramics, composites, surface and interface sciences, mathematics, computer science, metrology and engineering…. rigid separation of the different disciplines is becoming inappropriate ... barriers or boundaries between them are beginning to erode. The examination of elementary particles, atoms and molecules cuts across materials whatever their origin....”* (Kaounides, 1995: 15)

Such discipline-spanning knowledge and skills are often noted in connection with innovative industries and sectors. This is one reason why Hendry concluded that the issue of skill shortages is rather complex. Often the right skills might exist, but not necessarily the *optimum combinations* of skills.

More recently, Abicht (2009) presented results from a survey of 178 German nano-businesses. Finding that over half of the employees of these companies hold University degrees, he recognizes that this implies that the firms are highly research-intensive character. (The smaller the company, the higher the proportion of employees with such degrees.) The remaining employees are skilled workers (20%), master craftsmen and technicians (10%), with just under 10% in administrative or unskilled jobs. In terms of expectations, the firms thought that the share of skilled workers would rise with the shift from research/development to production/service. A significant growth in job numbers is projected, with personnel in small and medium-sized nanocompanies growing from 27,300 employees in 2008 to 43,200 by 2013. (Most of this growth is expected to be in the next two years!) Half of the companies intend to meet their demand for further education through external educational institutions. Abicht argues that cooperation with universities and R&D institutes is an essential means of knowledge transfer for nanotechnology companies, because of the need for interdisciplinarity. However, the companies reported that few knowledge providers have successfully adapted to the demands from this new industry. It was suggested that providers of further education have to respond in particular to the requirements of smaller companies.

Training and other courses have difficulties in determining how to combine more fundamental and more specific knowledge of the technologies and applications involved, and combining these with skills in project management and collaboration. The academic community may stress inter-disciplinary knowledge, while industry seeks to deploy application-specific knowledge (and complains about the limited development of skills specific to particular subsectors). Training bodies need information on the extent to which a particular depth of knowledge in each of the three sets of skills will be required by employees at different levels. (Hendry noted, for instance, the importance of intermediate skills at technician level.) Industrial success will require skills at all levels involved, and to the extent that there is a problem, it seems to be one of achieving an optimum balance of skills.

4.2. Skills and Product Cycles

The studies of nano-skills that have so far been generated are necessarily providing us with snapshots of SKIN at an early stage of industrial development. The skill requirements that we see now may provide only limited insight into future quantities and configurations.

Here we can recall the discussion of product cycles. Tether et al (2005) discuss skill requirements over three phases of the life cycle. (1) In the early, ‘fluid stage’ of the product or industry, the key skills are those of entrepreneurs (often combined with scientific or technical specialists, and skills in marketing). Production skills tend to be more general and adaptable, rather than specific and rigid, as production workers adapt to rapidly changing technologies and demand. (2) In a later ‘transitional stage’, with its shift from product to process innovation, management skills become more functional and ‘scientific’, whilst those of the workforce become more specific, with a more precise division of labour. New specialist equipment may at first augment the skills of skilled workers. But over the course of the mature phase of the industry the labour force becomes increasingly deskilled as equipment becomes familiar and routine. (3) In the last phase of the product cycle, production is increasingly ‘offshored’, to countries with lower costs of production (especially labour) – this offshoring pattern was classic for manufacturing industries, and seems to apply to some elements of modern services, too, as new IT can be used to link service suppliers and users. Some high value added knowledge intensive activities – design, ongoing R&D (e.g. for product differentiation and new products), marketing, and strategic management) – may well remain based in the home country. The skills involved are managerial command & control skills and for a small “elite”, while the bulk of the workforce has with low or unspecific skills (we would add, sales and logistics to this).

This approach has considerable virtues, but when we are considering a set of products such as those of nanotechnology – where the products of today’s nano-industries may well be critical inputs for a wide range of user industries – it makes sense to differentiate between the industries innovating core nanotechnologies, and those that are making use of these in applications. These latter “user” industries may themselves often be innovators, creating new applications and nano-enabled products and processes. Tether’s account is mainly focused on the core nanotechnology innovators and those of the user industries that are themselves highly innovative users of nano-capabilities.

Some authors (Green et al., 2007, Miles et al., 2012) went further in explicating the skills required to drive innovation through the various steps of the emergence of a new product or process. The innovator needs skills for:

- **Sourcing and selection of ideas** – skills requirements here are connected centrally with the identification, collection and filtering of ideas for innovation . Innovation managers (and employees) will ideally have an awareness of existing sources for innovation both within and outside their organisations, and an ability to ‘scan the horizon’ for - and develop relationships that will lead to - new sources of ideas and stimuli for innovation. An ability to interpret data (from market, consumer and competitor research etc.) and to evaluate the viability of innovation ideas is also crucial. Knowledge of and an ability to apply relevant IP protection mechanisms constitutes a further important skill. Once an innovation idea is selected for possible progression to development stage, skills in arguing for its viability and potential value – often in the face of strong competition from competing projects – become paramount.
- **Development of innovation ideas** – upon securing financial support for progression of an innovation idea, attention is directed to the practicalities of development. Here, skills connected with the assemblage of development teams, allocation and management of

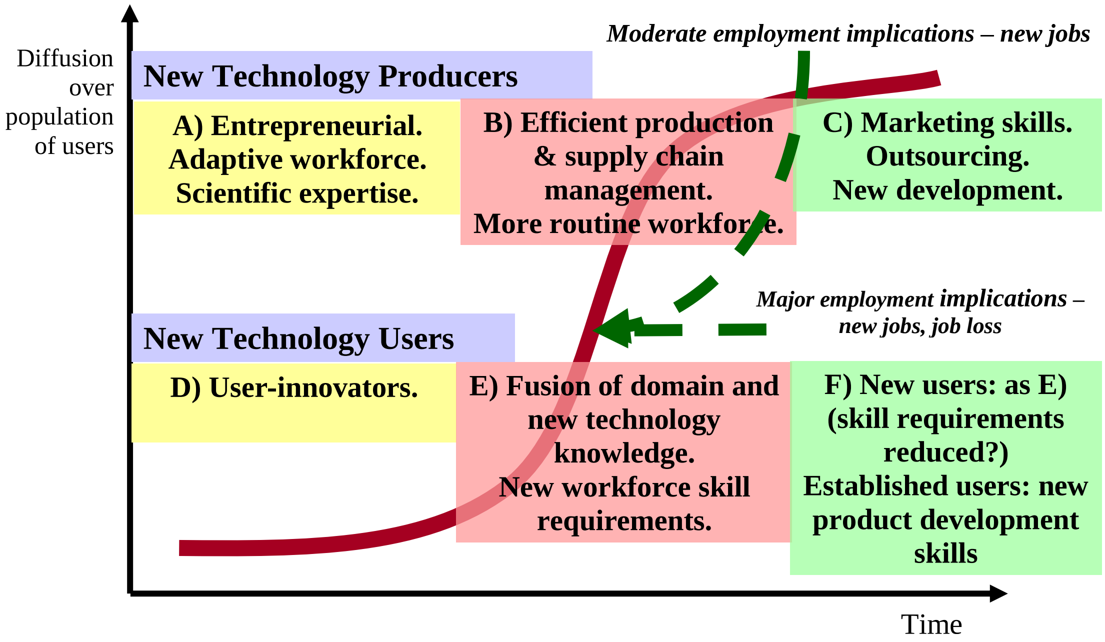
budgets and resources, generation of appropriate spaces and conditions for experimentation, sourcing and specifying complementary inputs, and establishing networks and partnerships are called into play. In the development of new artefacts/technologies, the sourcing of technical and design skills is often a central concern.

- **Testing, stabilisation and commercialisation** – a key skill at the ‘stabilisation’ stage is evaluation of risks and benefits of continued experimentation. Cost effective innovation requires an ability to recognise the optimal point at which to call a halt to prototyping and the comparison of competing alternatives. It also requires a good knowledge of the preferences and requirements of the intended user/consumer base and an understanding of the ways in (and extent to) which an innovative product or process will meet with anticipated needs. An understanding of the ability of potential users to derive benefits from an innovation (i.e., their ‘absorptive capacity’) is also necessary. Stabilisation and commercialisation requires that an innovating company has the skills in place to ensure reproducibility of an artefact or service at an acceptable cost and price (technical, engineering, design and marketing skills are often at the fore here). Commercialisation also requires that attention is afforded to ‘capturing value’ from an innovation – here, skills associated with managing risk and deriving appropriate roll-out strategies are foregrounded.
- **Implementation and diffusion** – marketisation, implementation and diffusion are frequently understood to be connected intimately with project management and technology transfer skills. Beyond these, skills in managing and coordinating value and supply-chain relationships, and in evaluating innovation practice and performance are crucial. Reflexivity is becoming an increasingly important component of innovation practise as firms recognise that collection and evaluation of data (i.e., knowledge management and intelligence generation) can result in the development of improved innovation processes.

These are pointers to the skills that are required for major innovations – though in general terms, the implications for nanotechnology development are easy to deduce. But it is apparent that the quantitatively most significant SKIN emerge as these major technologies are employed. For example, current occupational data suggest that around half of Europe’s workforce are using PCs and a third are using the Internet, which means that at least basic skills in a range of standard computer applications (word processing, spreadsheets, databases, browsers and search engines, etc.) are being utilised. These jobs have been transformed – while some clerical jobs have diminished substantially. These are wide-ranging changes, even if the new skills are ones that most professionals would regard as fairly basic – and that are becoming part of basic secondary education in most advanced countries. In contrast, more advanced IT skills, and the sorts of technical work that go with these, are much more restricted: only a few percent of Europe's workforce are IT professionals, and only half of these are actually located in IT sectors rather than user sectors.[13]

So we can also see user industries SKIN as evolving through the product cycle. Figure 5 presents a highly schematic illustration of how this might be represented, with the lead users being very much user-innovators, requiring high levels of understanding of the nano-tools as well as of their own application domains, and with users at later stages of the product cycle becoming progressively more numerous, and requiring quantitatively more skill in applying these tools in the particular domains.

Figure 4. Product Cycle: Skills and Employment



This is highly schematic, and it will be necessary to differentiate between numerous occupational positions – researchers, other engineers, technical support workers, production staff, managers, and so on, in order to map the entire range of affected occupations. Manufacturing and other application sectors will be supported by knowledge-intensive business services (KIBS), and by the supply of trained staff and knowledge inputs from education, training and research

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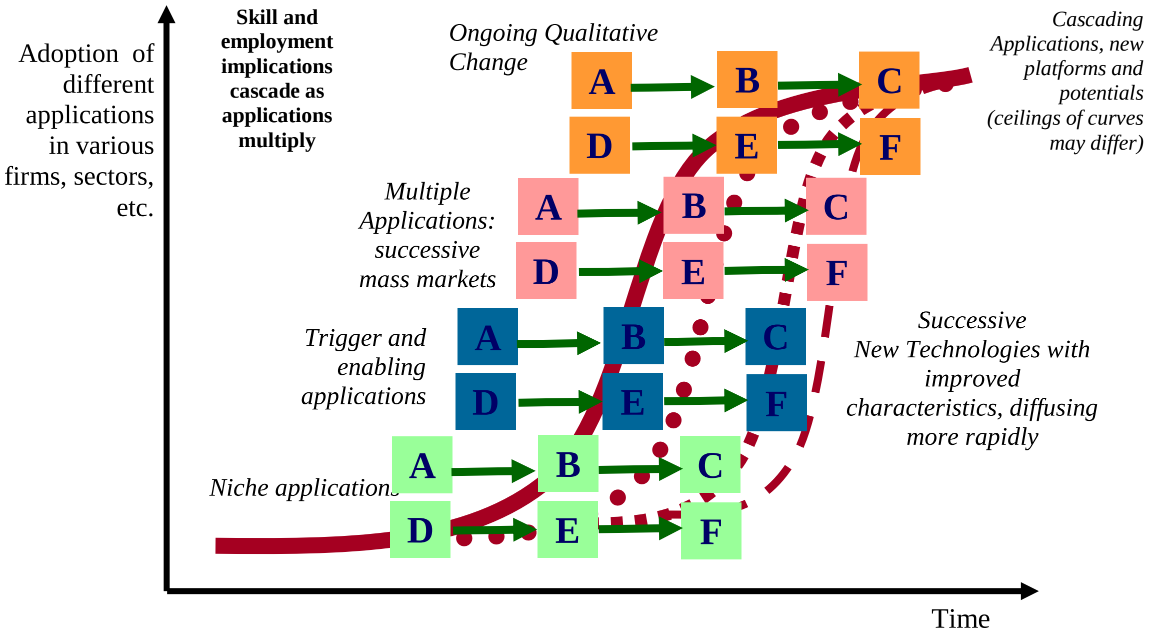
[13] CEPIS (2006) estimated that there are 4.2 million IT practitioners within the EU, while approximately 180 million people are using IT at work.

organisations. .But the point of the earlier discussion of multiple product cycles is that we are liable to see a series of S-curves as specific NT applications are developed and adopted in specific industry sectors. As these unfold, so requirements will be experienced through the (changing) occupational structures of these sectors, with various combinations of the skill classes emerging in producer and user sectors. Figure 5 combines Figures 3 and 4, to illustrate this.

Figure 5. Diffusion of Multiple Applications of new Core Technologies, and Skill Implications



The content will vary across sectors and applications in relatively predictable ways, but much of the balance across the three types of skill will be shaped by work organisation strategies – including those involving outsourcing and offshoring. New technologies alone do not dictate skill requirements and work organisation.

5. The Russian Experience

5.1. Overall Statistical Frameworks

Though Russia is in the vanguard of developing NT statistics, the work is still in an early stage. The effort is being made to explore distinct activities related to nanotechnology, namely R&D activities, development and use of nanotechnologies, and demand for personnel.

Development and implementation of nanotechnology statistics was initiated in 2008 by a team of specialists from the National Research University – Higher School of Economics (HSE) with the support of RUSNANO and in close cooperation with the Federal State Statistics Service. The proposed methodology for data collection and survey instruments were constructed with regard to the best practices of STI measurement and therefore based on the following principles:

- a systemic approach to measuring the scope of nanotechnology, providing its statistical research along the innovation cycle;
- development of a common conceptual apparatus, providing linkages and continuity of core indicators for various types of statistical surveys;
- series of statistical surveys covering different areas and aspects of the nanotechnology development and use;
- systematic statistical research based on regular surveys;
- harmonization with the recommendations of international organizations and other relevant international statistical standards.

The methodological approach adopted, at the outset of developing this area of statistics, was aimed at upgrading the existing system statistical reporting. Thus it mainly involved the inclusion of indicators of NT developments into existing statistical surveys. Later work has involved, in addition, the construction of various kinds of specialized surveys.
The overall indicator system covered:

1. The institutional structure of the NT field:
    - R&D performing organizations, innovation enterprises, firms producing nanotechnology-related goods and services (including small businesses).
2. Research and Development in NT:
    - expenditure on nanotechnology-related R&D;
    - results of nanotechnology R&D (including publication and patent activity; international cooperation in nanotechnology, IPR protection).
3. Innovation potential of NT:
    - nanotechnology development and use;
    - production and export of innovative nanotechnology-related products.
4. Commercialization of NT:
    - nanotechnology transfer (including exports);
    - acquisition of nanotechnology (including imports).
5. Manufacturing NT-related products:
    - sales of nanotechnology-related products (by their type);
    - exports of nanotechnology-related products;

- public procurement of nanotechnology-related products.

6. Investment in NT:
    - capital investments in nanotechnology;
    - fixed assets and technological infrastructure.
7. The size and composition of employees engaged in NT development:
    - number of employees by engaged in NT development;
    - nanotechnology R&D personnel;
    - demand for skilled workforce in NT.

The first step was taken in 2008-2009 when key definitions and classification approaches described above were developed and early pilot surveys identified a range of entities engaged in NT R&D and manufacturing. First indicators were integrated into annual R&D and innovation statistical surveys that allowed estimation of NT diffusion in the economy. The second step dates back to 2009-2010. It involves deeper analysis of the phenomena under a specialized pilot survey. It was built upon the previous phase and focused on a detailed study of the processes of development and use of NTs for production, institutional framework in this area, in particular the small business sector. The key problem at this stage was elaborating criteria for identification nanotechnology-related goods and services to evaluate actual NT market share and its potential growth. Finally, a third, ongoing, stage of statistical development of nanotechnology statistics is associated with the integration of the previous achievements and implementation of a comprehensive program of statistical surveying based on a single methodological approach.

5.2. Early Statistical Results on NT in Russia

Methodological approach and first results of the steps described above have been published in the annual statistical data books (HSE, 2013, 2012, 2011) and papers in Russian (Gokhberg et al., 2011) and in English (Gokhberg et al., 2012).

According to the available data there were 485 organizations engaged in nanotechnology R&D in Russia by 2011. Most of them were concentrated in the government (36.7%) and growing higher education (36.3%) sectors followed by the business enterprise sector (26.4%), whereas the share of private non-profit organizations in this field was negligible. This picture has remained almost completely intact compared to the findings of earlier studies (for details and figures, see here and further HSE, 2011, 2012). Nanotechnology R&D expenditure in 2011 barely exceeded 4.3% of gross domestic R&D expenditure in Russia. Annual growth in this amount by one-third was registered for 2008–2010, which is a significant increase against the background of general economic recession during that period. The number of researchers employed in nanotechnology R&D accounted for 21.1 thousand (5.6% of the total researchers' population in Russia) in 2011, which is 20% greater than that in both 2009 and 2010.

One of the key indicators of the economic impact of nanotechnology is the sales of nanotechnology-related products (goods and services). In 2011, total sales of nanotech products approached RUR 112.1 bln or 23.3% of the overall industry output. The 2011 figure demonstrates a positive trend: RUR 154.8 bln (29.5%). This amount is almost completely represented by ‘‘conventional’’ products manufactured with the use of nano-enabled processes (79.2%) or products containing nanocomponents (12.8%). As occurred, elementary nano-objects and nanodevices are often manufactured by chemistry and R&D sector (over two thirds of all nanotech manufacturers) as unique prototypes or small-scale pilot series, though the share of such products is rather small (7.2%) as well as that of specialised equipment for NT (0.7%).

The output of innovative (i.e. those either newly introduced or significantly modified) products related to nanotechnology was RUR 63.7 bln in 2011, of which 19.4% was exports. Manufacturing of goods with the use of nanocomponents and nano-enabled processes is concentrated mostly in medium low-tech sectors due to high (overestimated) sales in oil and gas refining where nano-catalysts are widespread that goes in contrary with many forecasts that bet for elementary nanoproducts (mostly manomaterials). Although the inclusion of these products into ‘‘nano’’ categories is debateable (Gokhberg et al., 2011), respective figures additionally contribute to positive dynamics of nanotech production. The innovation survey results suggest that innovative nanotechnology-related products are characteristic of such economic activities as the manufacture of food products, machinery and equipment, motor vehicles, radio, TV, and communication and medical equipment.

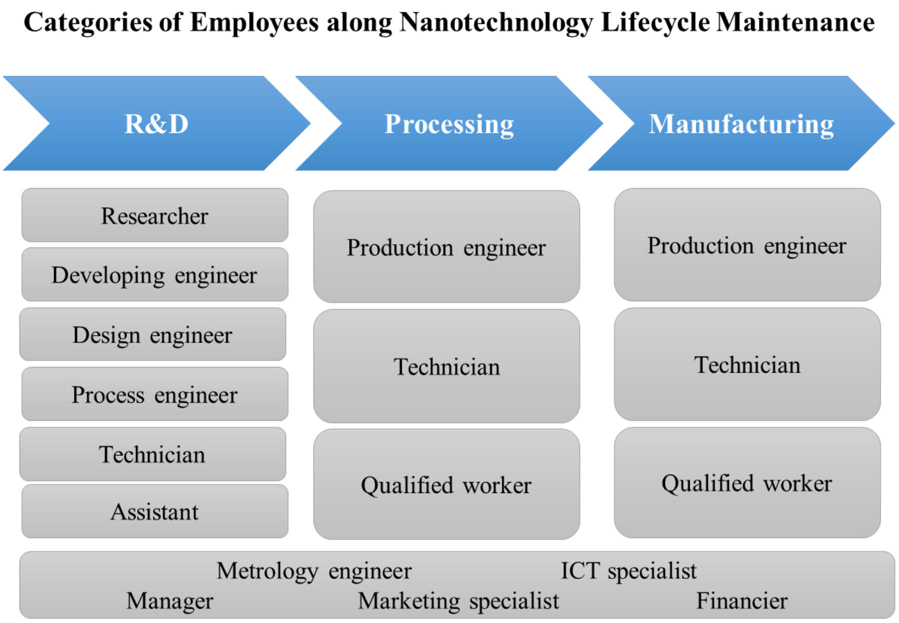
5.3. Skills and Employment

Building on the approach to SKIN discussed earlier HSE has been undertaking studies of current and future skill requirements for NT. A framework of future paths of development rather like those outlined schematically above has been developed – see Figure 6. This allows for estimates to be made of the number of personnel required, and of the skill profiles required of them.

To get data on required competencies two strategies were used: (1) indirect assessment of the quality of education achieved by an empoyee and (2) direct skills assessment in accordance with the competence profile describing professional duties performed by an employee (further see

Shmatko, 2013). Using the analysis of areas of NT development and application mentioned above, and expert panels, estimates have been arrived at concerning the sorts of educational profile required in a range of related areas, and of the occupational and skills structures involved. Details of this work will form the basis of a future Working Paper. A few highlights, however, can be mentioned.

Figure 6. Occupational Groups over the course of NT development



Source: based on (Schmatko, 2012)

The most important is that the main requirement for almost 50% of personnel is need for highest-level of formal qualifications. Holders of PHD and Masters degrees in natural sciences constitute around 25-30% of all required personnel, another 20% are holders of Master degrees in multidisciplinary research. In absolute numbers that means that in 2009 around 3000 students were focusing on one or other aspect of NT, those some ten times this number were developing relevant skills in broader disciplinary areas.

6. Conclusions

The paper suggests some major points for statistical and forward-looking analyses of emerging area such as nanotechnology.

As for statistics, we should set more stringent criteria for classifying manufactured products to a particular standard product group, otherwise the risk of their broad interpretations and errors in completing the reporting forms. Although the proposed methodology allows us to "cleanse" the value of the corresponding figure at the expense of the exclusion of the cost of elementary nanoproducts purchased or containing semi-complex problems related to NT products is preserved. To solve this problem, we might encourage survey respondents to include in NT only those types of products in which nanomaterials are integrated into the product, so that their removal leads to a deterioration of functional properties or destroying the product. This will eliminate the overstatement of the volume of shipments of products related to NT, to improve overall accuracy of the estimates.

Secondly, it is important to more clearly differentiate the differences between the groups of various types of these products. For example, a group of goods and services produced on the basis of technological processes using NT, could be attributed virtually all of the products manufactured from NT, including elementary nanoproducts and other nano-enabled products because the use of nanotechnological processes, by definition, involves work with the substance, i.e. modification of the size, shape or structure of matter forming the product. In addition, there is a question of taking into account the cost of such products. In particular, the purification of petroleum products may involves using special nanocatalysts and their subsequent processing with chemical additives (including those containing nanostructures). As a result, the final product acquires new qualities. Determining the value of these products becomes a separate task that requires special calculations and develop specific conventions. Therefore, for statistical purposes it is proposed to exclude oil products from the category of NT related products. We propose that the name of the group be altered, so that there remains in it only those services applied to achieve a certain quality that is impossible to attain without the use of NT (the above-mentioned services for accurate medical diagnosis, etc.).

Finally, the current version of the reporting format provides only a sample group of products, characterized by the use of a factor of production – special equipment for NT. However, one of the decisive conditions for the development of NT is also the availability of basic raw materials for production of elementary nanoproducts. In order to improve the methodological basis of statistical observations in the field of NT, we propose a collective grouping of "goods, works and services related to NT," position "basic raw material for NT." Subsets of activities here will need to be introduced as events unfold.

Turning to Foresight, and especially to the longer-term examination of SKIN, we have suggested viewing developments in terms of a cascade of product cycle and diffusion curves. A succession of job creation and skill requirements are liable to emerge, as the core nanotechnologies are enhanced by complementary technologies and by integration into various application areas, and as dominant designs and common platforms and standards are established. The larger employment effects are liable to lie in these application areas, though this is not to underestimate the potential significance of the heartland industries (consider the importance of IT firms in today’s world). Skill requirements evolve as successive applications emerge; it is plausible that applications will be further combined into innovations that themselves form the basis for new products and industries.

“Calibrating” this approach requires estimates of the speed of uptake and the extent to which transformative processes are themselves transformed through NT. In addition to the estimation of which industries and applications take off at which speeds, it will be necessary to confront the arguments about how revolutionary NT will be – will it essentially be an extension of existing nanoengineering techniques, or embody the more radical visions of molecular engineering and “bottom up” NT. Disputes about these perspectives become rather important for forecasting beyond the medium term (5-15 years) – and even within it. Scenario analysis may be one response to such disputes, with alternative scenarios reflecting the realisation of one or other viewpoint.

There is another issue that is important even for medium and shorter-term analysis, yet which is liable to be highly relevant for national policymakers (and for managers, too). This is the spatial location of developments, especially international variations in the dynamism with which new technology is developed and diffused. Interest and investment in NT is very high in some parts of the world – including BRICS such as Russia and China. Countries that were largely “lagging” in terms of the earlier phases of the IT revolution are making huge efforts to be at the frontier in nanoscience. There are liable to be several results of such activity, which makes for yet more uncertainty when it comes to anticipating future trajectories:

- The overall pace of development is liable to be accelerated by sharpened competition and greater levels of investment (even if there is bound to be some redundancy in efforts).

- We may see greater risks taken – and some problems that might be avoided may thus confronted sooner or more acutely than would otherwise be the case, too.[14] This could lead to reactions such as sudden tightening of regulations or public opposition to NT development.[15]
- The areas and modes of application of NT are liable to reflect factors such as the leading industries and styles of organisation of the countries that are taking the lead. (Issues such as public procurement influences and protection of infant industries could be influential here.) This might affect skills issues, for example whether fast-developing applications are shaped to fit more or less highly skilled labour forces and available capital.
- More generally, competition may mean that some regions and countries simply lose out as sites for the development – and even for the application – of some or many new NTs. There will be potentially substantial implications for demand for skills in the successful and unsuccessful areas.

Turning to the issue of NT Foresight, the complex issues in play means that it makes little sense to pin one's hopes on the accuracy of a single forecast – especially as longer-term developments are considered. Scenario analysis is a tool that can help tackle, for example, the different possibilities that might evolve in terms of the global division of labour in NT production and use, the scope for development limits of different types of NT, the emergence of wild cards, etc.

For practical policy making, such analyses can do more than shake complacent (or resigned) assumptions about the inevitable place of one's country or region in this division of labour. It can point to forms of horizon-scanning that should be undertaken continuously, and "weak signals" that should be monitored in order to provide early warning of how far events are moving the NT world in the direction of one or other scenario. Typically, the future that eventually emerges will contain elements of several of the scenarios examined in a well-designed scenario analysis – though there are always liable to be surprises as social innovators as well as the more familiar technological innovators introduce yet more novelty into the picture. We may be able to identify

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[14] A study of NT-related deaths that attracted much attention is Song et al (2009), though commentators have argued that the deaths in this case resulted more from general health and safety failures rather than anything new connected with NT; for a discussion of potential pitfalls in Foresight-like assessment of NT risks see Williams (2005).

[15] NT may be affected by problems in other high-tech activities – such as biotechnology, or the emerging field of 3D printing – where the possible use of these printers to manufacture weapons (by "ordinary people" rather than established gun manufacturers) has recently hit the headlines – see for example the story "3D-Printer Company Sells to Gun Companies, But Not Desktop Weaponeers". Online: http://www.wired.com/dangerroom/2012/10/stratasys-followup/ (accessed 20/10/2012).

a range of plausible alternatives, but we cannot hope to predict every development – not even every important development.

This is an argument for ongoing attention to developing trends and trajectories, rather than a counsel of despair. Statistical analyses provide a vital base for more well-grounded foresight studies. Being prepared to confront alternative futures is also required, to enable more effective response to unexpected events. One thing that we can be sure of is that that we will encounter such unexpected events.

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