Assessment Tools for the Management of New and Emerging Science and Technology: State-of-the-Art and Research Gaps

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Summary

New and emerging sciences and technologies (NES&T) are characterized by the combination of great uncertainty and (hopefully) great potential. At an early stage it is unclear if and how their potential might be realized. 'Best practice' as it has evolved cannot be the guideline for what is breaking through existing practices. So how do researchers and technologists, R&D managers, staffs in funding agencies and policy makers actually assess NES&T and manage high-risk projects, what tools do they use? Existing literature reviews do not necessarily address assessment of *new and emerging* technology. Our paper provides a framework to quickly access the majority of the relevant bodies of literature, among others: strategic management of S&T; strategy; R&D and innovation management; Futures studies; organization studies; S&T policy; and bibliometrics. We review literature on three functional groups of tools: 'anticipatory tools' (including foresight exercises, bibliometric analyses, scenario planning); tools for 'anticipatory coordination' (including assessment of discontinuity caused by new disruptive technologies; assessments of 'hype-cycles'); and portfolio and project management tools. We conclude that most authors stress that tools need to be practical while they are often used to support assessments based on personalized experience and competence. This has an impact on adaptation of existing, or development of new, tools. We point at a major gap in the literature, i.e. the lack of assessment tools for open-ended science, and suggest exploring the feasibility of tools to assess the richness of emerging linkages between actors and possible uses, and mapping hype-disappointment patterns in order to articulate strategy.

Introduction

Assessment tools for new and emerging science and technology (NES&T), with their inbuilt uncertainty about their future development and value, are increasingly important, with the challenge of new developments felt in industry, the health sector, and the research world. There are various attempts to adopt and adapt existing assessment and management tools and approaches, or develop new ones like the foresight exercises since the early 1990s. Tools for technology assessment and management are being used in strategic management of the whole business and organization, for instance, for analysis of the operating environment of a firm (industry) and the remote environment (economic, legal, political, social, and technological trends). They are also being used in strategic analysis, specifically, to generate and evaluate alternative strategies (Clark 1997:424; Frost 2003:57-58). The various existing technology management and general technology assessment literature reviews cover the period since the mid-1970s quite well, however in doing so they do not necessarily address assessment of *new and emerging* technology. Our paper, while building on existing contributions, explicitly focuses on these NES&T, providing a framework to quickly access the majority of the relevant bodies of literature. In this introductory section we characterize existing efforts in various fields at literature reviews on assessment tools and, against this background, outline the scope of our paper and the criteria for the selection of literature.

Existing contributions. One limitation of existing reviews in the technology management and general technology assessment literatures is that their scope is that of a single organization. This limitation becomes the more important when addressing the challenge of new science and technology which most often emerge in the interaction between a variety of actors. In the technology management literature, Probert et al (1999) provide a five process model for the management of technology within which they locate various techniques and tools. Technology assessment, which is the first step in the model, contributes to the identification of technologies which are (or may be) of importance to the business. Brady et al (1997:421) list references to specialized papers and literature reviews on technology management tools from the period 1989-1997. Liao (2005) offers a literature review of technology management methodologies published in the period 1995-2003 with some discussion of technology assessment tools. Likewise, a rather broad perspective characterizes the strategic management of technology reviews of Husain and Sushil (1997) and Kurokawa et al (2005). Hussey (1997) presents a 'glossary of techniques for strategic analysis' (title) but the purpose of the paper is not so much to comprehensively list and define techniques but to give further references to tools such as Delphi, experience curves, learning curves, and scenario planning. However, some of the references are rather old (for example for Delphi-type foresight tools) (Hussey 1997:103-104).

In the general technology assessment literature, Henriksen (1997) compiles and presents a comprehensive toolkit of assessment techniques that can lead to improved and more effective management of enterprise product, process, and supporting technologies. She locates technology assessment at the corporate level, its task being to evaluate the aggregate technological capability of the enterprise and to facilitate corporate strategic technology planning. Van den Ende et al (1998) review the various approaches to technology assessment over time. This article is a de-facto literature review but the authors' focus is broader then assessments of NES&T.[1]

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[1] On the topic of TA, cf. also the special issue in *Technological Forecasting and Social Change* on 'The End of OTA', (1997) **54** (2-3), February - March.

There are by now *tool-specific* literature reviews and special journal issues. For instance, over the past ten years special issues on foresight have been published in *Long Range Planning* (1996) and *Technological Forecasting and Social Change* (1999), literature reviews on bibliometrics in *Scientometrics* (2001; 2003), special issues on front end of innovation/really new product development processes in the *Journal of Product Innovation Management* (1998), a special issue on portfolio management in *R&D Management* (2001), and literature reviews on forecasting in the *International Journal of Forecasting* (1996) and *Technological Forecasting and Social Change* (2003). With the growing importance of such tools one is thus faced with a widening range of journals to scan for state-of-the-art information, spanning the S&T policy, R&D and innovation management and sociology of S&T literatures. It is not always evident from the title of the papers whether they address NES&T.

Scope of this paper. At present there is no comprehensive literature review that would provide a framework to quickly access *all* these bodies of literature. Our paper fills this gap. Our understanding of 'assessment' accommodates three functional groups of tools:

- There are tools used to articulate what the future will be like – at the level of a science or technology, but also the future environment of an organization or future characteristics of society (such as customer demand). Such 'anticipatory tools' comprise, for example, foresight exercises, bibliometric analyses, and scenario planning.
- There are tools that go beyond stating what the future could be like, and help assessing actions on the way there. These tools for 'anticipatory coordination' comprise, for example, assessment of various forms of discontinuity caused by new disruptive technologies, and also the so-called 'hype-cycles', a new assessment tool.
- A third category deals with portfolio and project management. Here we have tools for comparative assessments of radical innovation projects, and project management.

This functional categorization has some similarities with the one recently provided by Lichtenthaler (2005) with respect to private sector technology intelligence (TI). TI tools have an 'extrapolative' function (using benchmarking; roadmaps; and portfolios), an 'explorative' function (Delphi; scenario analysis), and a 'normative function' (experience curves; scenarios). While 'assessment' as a term is more widespread in public sector science, S&T policy circles, and at the level of scholarly analysts, especially in sociology of S&T, in firms these assessment activities often are part of strategic planning, and sometimes called 'entrepreneurial planning' or 'applied technology assessment' (Berloznik and van Langenhove 1998:25-26), 'technology forecasting', 'competitive technical intelligence', or 'technology intelligence' (Lichtenthaler 2003, 2004, 2005). Tools such as scenarios, quantitative conference analyses, experience curves, flexible expert interviews and expert panels are often so tightly integrated into the processes of strategic technology management 'that they are no longer perceived as specific methods of TI' (Lichtenthaler 2005:391).

We do not question this integration but focus on those tools that, while being used for strategic management, have one or other of the *science* or *technology* assessment functions outlined above. Our understanding of tool is that tools are (to some degree flexible) procedures with instrumental character, i.e. implying some collectively shared goal (which can be another instrument itself, such as a roadmap, or defined in a rather open-ended way, such as brainstorming sessions), and collective character, i.e. they are known to, and applied by a number of people, be it an expert group or a more loosely defined group. Because of the range of tools to be taken into consideration we had to leave out a number of areas. At the level of public R&D programmes we have found very little in terms of tools used to assess project proposals, or sketch out future directions of the programme. There is general literature on priority setting in public sector research which we note in passing (MacLean et al 1998). Georghiou and Roessner (2000) review tools and methods for the evaluation of technology programmes in the public sector. They exclude evaluation procedures in science, such as peer review and bibliometrics, and methods for *ex ante* evaluation of project proposals, which we are interested in. We exclude assessments 'after the fact', such as comparative assessments of existing technology to formulate and implement procurement policy (cf. as an example Hailey and McDonald 1996 on procurement of diagnostic imaging technologies in health care), and business impact assessment (cf. Pretorius and de Wet 2000).

Criteria for the selection of literature. The journals we have selected are from eight different areas. Naturally, we included the strategic management of S&T literature, as well as the broader R&D and innovation management literature. We added the general management literature, but also the more social sciences influenced management and organization literature, which have contributed insights into the tensions underlying assessments of NES&T. Some parts of the strategy literature are tools-oriented, and contain interesting contributions. At the level of the firm and units, scholars have explored organization and management of innovation processes using concepts such as internal venturing; new business development (NBD); corporate venturing; corporate incubators; corporate entrepreneurship; new product development (NPD); etc. (the terminology is rather unstable). The focus is on efforts necessary to organize for development and/or commercialization of NES&T, which we do not discuss here.[2] Another complex is the S&T policy literature, qualitative science studies, and quantitative, indicator-based science studies (bibliometrics, scientometrics, and patent analysis literature). Finally, we selected a few contributions from futures studies as distinct from the strategy management literature. We selected these journals using criteria such as being considered key journal in its field; containing publications relevant for the topic; and being published in either Europe or North America. Among the strategic management of S&T journals, for instance, *TF&SC* was at the top of the lists of top sources of 1986-88 and 1995-98 technology forecasting/technology futures articles (Porter 1999:24, 25), while *Strategic Management Journal* was ranked among the top five management journals of 1981-99 with respect to number of article citations received, and was one of the fastest growing journals in that period with respect to citations received (Podsakoff et al 2005:476, 486). *TF&SC* is the most represented journal in our review. *Scientometrics* was at the top of the top-20 most productive journals in the scientometrics, bibliometrics, and informetrics literature as identified by Hood and Wilson (2001:305). Generally acknowledged key journals with a broader management focus, such as *Harvard Business Review*, were only considered if the journal offered useful contributions.

Selected journals. In the above eight areas we covered the following journals:

- (1) **Strategic management of S&T** literature: *International Journal of Forecasting*, *International Journal of Technology Intelligence and Planning*, *Long Range Planning*, *Strategic Management Journal*, *Technology Analysis & Strategic Management*; *Technological Forecasting and Social Change;*
- (2) **Strategy** literature: *Strategic Change*, *Strategy and Leadership*;

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[2] Some useful references are, Kassicieh et al. (2002); McDermott and Colarelli O'Connor (2002); Rice et al (1998); Anderson and Tushman (1990); Vanhaverbeke and Kirschbaum (2002). Cf. also the consultancy-style literature as represented by Miller and Morris (1999: 24, 214; 280-281).

- (3) **Broader R&D and innovation management** literature: *Enterprise and Innovation Management Studies*, *IEEE Transactions on Engineering Management*, *International Journal of Technology Management*, *Journal of Business Venturing*, *Journal of Engineering and Technology Management*, *Journal of Product Innovation Management*, *R&D Management*, *Research-Technology Management*, *Technovation*;
- (4) **Futures studies**: *Futures*, *Futures Research Quarterly*;
- (5) **General management** literature (only key contributions): *California Management Review*, *European Management Journal*, *Harvard Business Review*;
- (6) **Management and organization** literature: *Administrative Science Quarterly*, *International Journal of Management and Organization*, *Organization Science*;
- (7) **S&T policy** literature **(including science studies)**: *Research Policy*, *Science and Public Policy*, *Science Studies*;
- (8) **Bibliometrics, scientometrics, and patent analysis** literature: *Scientometrics*.

Structure of the paper. Our first section deals with 'anticipatory tools'. It covers foresight in public research organizations and programmes and the private sector and the tools used in foresight, especially Delphi; scientometrics, bibliometrics and informetrics as examples of methodologies of statistical analysis using S&T indicators; and scenario planning. The second section is dedicated to 'tools for anticipatory coordination'. We discuss roadmaps, hype-cycles, market performance trajectories and learning curves. The third section is about 'tools for portfolio and project management', which includes portfolio management, project selection and evaluation tools, and tools for managing front end of innovation processes. Since we also focus on tools adapted to assessment of NES&T, we found it on occasion useful to introduce these tools by outlining how they are normally being used (such as roadmapping or portfolio management). This of course is no attempt at capturing the whole range of the uses of the particular tool. The remainder of each entry is structured around uses of the tool for assessment of NES&T, remaining methodological challenges, and/or its limitations where remarked upon in the literature. The three thematic sections are followed by a concluding section where we summarize our results, point at gaps in the literature, and use some lessons derived from the discussion of the tools to point out possible ways of responding to this gap

Anticipatory tools

Foresight and tools used in foresight

Definitions. Foresight (FS) has a long tradition in the private sector; from here it was taken up by actors in the public sector. Technology FS as currently practiced in the private sector is 'the systematic recognition and observation of new technologies ('weak signals') or existing technologies, the evaluation of their potential and their importance for the competitiveness of the company, and the storing and diffusion of information' (Reger 2001:535). Empirical studies of strategic planning or strategic management of technology that tackle technology FS have been missing (Reger 2001:534) but their number is now slowly growing, even if the bulk of work is limited to large corporations (Lichtenthaler 2003; 2004; 2005; Speith 2004). Martin (1995) defines FS with respect to national exercises more broadly as 'the process involved in systematically attempting to look into the longer-term future of science, technology, the economy and society with the aim of identifying the areas of strategic research and the emerging generic technologies likely to yield the greatest economic and social benefits' (Martin 1995:140).

Tools. FS is a rather generic term and makes use of a number of methodologies, tools, and techniques, often in combination. Tools and techniques that have been used are as diverse as panels, Delphis, scenarios, brainstorming, la prospective, impact matrix, generic/critical technology lists, relevance trees, morphological analysis, etc. The Technology Futures Analysis Working Group (TFAMWG, 2004) provides an overview and systematical description of foresight and technology intelligence tools used in the public sector and private industry (TFAMWG, 2004: 289). Some of these techniques have come to be used almost synonymously with FS, such as Delphi (Grupp 1999). National FS exercises fall into three categories (Georghiou 2001), Delphi-type studies (1990 German Delphi; 1993 and 1999 South Korean Delphi; 1994 French Delphi), mixed studies (1989 Dutch exercises; 1994-95 UK Foresight), and panel/scenario/critical technologies-type studies (1991, 1993, 1995, and 1998 US Critical Technologies exercises; 1995 French 100 Key Technologies; 1999-2000 UK Foresight). Some of these exercises have been described and analyzed in two special issues: *Long Range Planning* (1996) **29** (2); *Technological Forecasting and Social Change* (1999) **60** (1).

There is a large body of literature on Delphi as the most important tool used for aggregation of views on the future in FS. Tichy (2004) identifies and describes three types of Delphis (the 'classical, 'policy', and 'decision Delphi'). Mitchell (1991:348-350) gives an overview of the techniques and applications. Rowe and Wright (1999:354-355) list the key features of Delphi, which make it a better tool than panels where experts meet face-to-face: anonymity; iteration (due to the at least two rounds); controlled feedback (from round one to round two); and statistical aggregation of group response. Gupta and Clarke (1996) present a bibliography of Delphi-related literature from the period 1975-1994.

Johnston (2002) observes that Delphi studies have come to lose their initial dominance. FS has started making greater use of tools that allow for such articulation of multiple futures, such as scenario building. In older FS exercises, experts were involved; recently there has been a move towards inclusion of other stakeholders from broader society: voluntary organizations, consumer groups, or pressure groups. Consequently, a phrase like scenario building has become more visible, almost replacing 'foresight'.

Benefits and Limitations. In the 1990s FS became one of the most popular tools in S&T policy making for selection of promising research areas and emerging technologies on which to target limited resources, in order to derive the greatest benefits (Martin 1995: 139, 165). In the third-generation, process view on FS, the quality of the dialogue between participants from the business, science, and government sectors is stressed, as their interactions are an important factor that can influence take-up of results of a particular foresight exercise by various stakeholder communities (Barker and Smith 1995:22; Godet 1989:47, 48; Martin 1995:140; Reger 2001).

At the level of the FS exercise, its organization has been criticized (Barker and Smith 1995) and the underlying models of innovation (variations on the linear model) (Tait and Williams 1999), at the level of FS tools, the limitations of expert opinion methods, such as Delphi (Tichy 2004:344, 360), inaccuracy of the interpretation of the foresight data, and high degree of complexity of the relationships between the various forecasts. FS can be used for identifying NES&T but this does need not immediately translate into action. Analytical information has often had much less influence on decision processes than analysts would hope for (TFAMWG 2004:294), and sociologists of S&T have identified the way how FS is embedded in the research system as the key to its effectiveness (Rip and van der Meulen 1996). A number of authors have shown how to use statements generated in FS exercises in order to formulate roadmaps for the facilitation of monitoring and evaluation of foresight and how to create roadmaps for private organizations (Barker and Smith 1995; Saritas and Oner 2004; Tait et al 2000).

Van der Meulen (1999) categorizes tools used in national-level FS exercises from the viewpoint of a sociologist of S&T, i.e. against the background of the articulation of the dynamics in FS. Based on an empirical study of future studies in the Netherlands, he describes the dynamics of FS in terms of a force triangle constituted between the creativity of visions of the future (creativity to challenge strong beliefs and vested interests), the expertise of scientists and engineers to link up the possible futures to present technological challenges, and the interaction between experts and non-S&T experts (users, such as industry, government, society) in order to articulate shared visions. FS tools can be located within the three continuums that are created between any two pairs of these three poles. Between the poles of expertise and creativity, van der Meulen locates panels - essays - Delphi - scenario writing - science fiction; between creativity and interaction/alignment, science fiction - brainstorming - la prospective - workshops; and between interaction/alignment and expertise, workshops - conferences - impact matrix - panels (van der Meulen 1999: 18-19). The added value of van der Meulen's contribution is that people involved in the preparation of FS exercises are able to identify benefits and disadvantages to be had from use of different tools: do they tend to support one pole more than the opposite one? The author's premise is that for FS to contribute to strategic S&T management, the three poles must be balanced – all of them must leave their mark on the FS exercise but if one is dominating, their might not be the desired outcomes.

Bibliometrics, scientometrics, patent analysis, and data mining

Literature. One of the main journals for bibliometrics, scientometrics, and patent analysis is *Scientometrics*.[3] The literature here can be broadly grouped into three categories: overview and discussion of tools; applications in the science and technology policy context; and applications in strategic management of S&T. We have analyzed publications falling under the applications-oriented categories, and discuss below a number of reported uses for bibliometric tools.

Identification of frontier areas. Statistical analysis of S&T indicators has been presented as a way to identify frontier areas of research and state-of-the-art. Frontier areas of research are those, which experience in a particular time period a significant increase in research output in comparison to a preceding period. Within these frontier areas, active research topics can be identified. The assumption is that if high activity, as in frontier areas, is taken as an indicator of importance, then S&T performance indicators can be used as a tool for allocation of resources. Several authors have proposed ways how to identify frontiers and topics with bibliometrics, such as Bhattacharya et

[3] We add other, related fields: Technometrics and librametrics are lesser known terms (Hood and Wilson 2001); a new bibliometrics field since the 1990s is concerned with world wide web information (Bar-Ilan 2001).

al (2000), or Schwechheimer and Winterhager (2001), who suggest using co-citation mapping in combination with expert judgment. These authors also point out that in practice it is quite a complex and difficult task using bibliometrics and similar methods as policy aids.

Degree of interdisciplinarity. Another aspect of interest to S&T policy makers is the degree of interdisciplinarity or multidisciplinarity in emerging S&T, such as the 'nanosciences' and –technologies, as this allows for better disciplinary targeting and evaluation of programmes. There a number of approaches to measuring interdisciplinary, such as co-word analysis of discipline-specific keywords; co-classification analysis of discipline-specific headings; co-author analysis of disciplinary affiliations of co-authors; citation analysis of citation between papers of different disciplines; and journal classification. Schummer (2004) advocates co-author analysis, i.e. looking at the departmental affiliations of authors of a paper, as this approach considers the social aspect of interdisciplinarity and focuses on research practice, i.e. the successful research interaction between different disciplines (Schummer 2004:435-438).

S&T relationships. A main question in S&T policy is: To what extent do patents indicate the uptake of research advances by industry? For S&T analysts and practitioners of bibliometrics, this translates into the question of how it is possible to apply bibliometric citation analysis (which focuses on academic papers) to patent citations. There is a growing literature on the analysis of science-technology relationships in emerging areas, such as nanotechnology, by way of patent analysis, also known as 'patent bibliometrics' or 'patent citation analysis'. Hullmann and Meyer (2003) provide an overview of bibliometric and patent studies of nanotechnology, using indicators such as publications and patents. Kayal and Waters (1999) give an overview of technology indicators in patent citations. A number of Meyer's contributions in *Scientometrics* (2000a, 2000b, 2001) focus on patent bibliometrics with respect to nanotechnology and 'nanoscience'. Meyer's conclusion is that patent citations do not give insight as to the direction of potential knowledge flows (Meyer 2000a:152; 164; 165; Meyer 2001:166), because the linear understanding of technological progress, as embodied in the concept of science-based technologies, is misleading. Cited papers are rarely the key source of the idea that led to the technical invention. Nano-science citing university nano patents rely on nano-publications authored in the university system or non-industrial research centers. MNCs cite their own research in their patents. Increased patenting activity in a science based field thus does not mean industry taking up developments coming from the academic sector (Meyer 2001:176). Still, the crucial question is if perhaps certain technological fields, such as nano-instrumentation, need support because scientific activities would then pick up, eventually leading to advances in other technological fields (Hullmann and Meyer 2003:525).

Competition monitoring. In companies, PA and bibliometrics are seen as complex and costly and are only used to address *specific* strategic questions, such as analysis of competitors (Meyer 2000a:152) and open scanning for new technologies (Lichtenthaler 2005:391; Liu and Shyu 1997:673). In the 'technology cycle time' (TCT) approach, a more recent age of the patents cited on the front page of a patent document indicates that one generation of inventions is more quickly replacing another. The tool can be used to distinguish who is developing new technologies from who is improving old ones, thus pointing at future leaders in technology and product development (Kayal and Waters 1999:127, 128).

Strategic management of S&T, especially in the private sector. Data mining, as a text analysis technique, has been presented as an aid in strategy formulation and implementation. Data mining helps answering the following questions: What S&T is being performed? Who is performing this work – with respect to companies, universities and individuals? Where is it being performed? What messages, patterns, and relationships can be extrapolated from the databases mined? What shifts over time of technological emphases are there? What is not being performed? (Kostoff and Geisler 1999:505; Porter and Detampel 1995:240).

Limitations of the tools. The obvious point about these techniques is that by their very nature, most of these tools identify what *has been published*. But this may not capture all that is new and emerging. Signals of potentially emerging S&T are discussed at conferences and workshops before being published, while on the other hand, patents do not necessarily refer to research fronts in science. Hence there is a retrospective bias to such methods. In addition there are is the constant challenge of unclear boundaries and terminologies characteristic of emerging areas: The dissent among practitioners as to what 'nanotechnology' means, for example, has consequences on how the field is indexed in different databases (such as ICI and INSPEC). With nano being the smallest common denominator, bibliometric and patent analyses risk the danger of becoming too imprecise and ineffective for, say, strategic planning (Hullmann and Meyer 2003:508; cf. also Bengisu 2003:477).

Bibliometric and data mining approaches are often underused and poorly understood, partly because the techniques developed in the literature are too complex for practical use (Kostoff and Geisler 1999:497). A number of publications contain suggestions how to address the issue of improving practicality. Eventually, a combination of statistical and qualitative tools must be achieved as this offsets *mutual* shortcomings. Porter and Detampel (1995) want bibliometric methods combined with other forms of information, such as semi-quantitative and expert opinion. Kostoff (1999) suggests organizing interdisciplinary workshops of experts on specific central themes, with results of data mining exercises being available to broaden the search for promising research directions (Kostoff 1999:595; see also Kostoff and Geisler 1999:504). Smalheiser (2001) demonstrates how data mining can be used in combination with scenarios in order to anticipate *possible* new technologies or new uses for existing technologies, which are not even emerging yet but might influence future directions of ongoing research.

Scenario planning

Literature. Scenarios have come to be popular and scenario-based planning is used in a variety of organizations and for various purposes, ranging from the UK take-home drinks market (Warren 1995), business futures after political changes (Blanning and Reining 1998) to information and telecommunication behavior of residential users (Mante-Meijer et al 1998), interactive TV in Europe (Jacobs and Dransfield 1998) and biotechnology (Sager 2001). There are special issues in *Long Range Planning* (1996) **29** (2), *Technological Forecasting and Social Change* (2000) **65** (1), and a cluster of papers in *Technological Forecasting and Social Change* (2005) **72** (2). For short historical accounts, cf. Godet and Roubelat (2000); Mercer (1995); and Bood and Postma (1997). Scenarios can be drawn up in order to articulate possible futures and their socio-economic, environmental, and policy-related challenges; activities being (or to be) undertaken could then be shaped so as to respond to these perceived challenges. Scenario-based planning in private organizations addresses a number of strategic, firm-level objectives, such as the development of a robust set of strategies (Mercer 1995:85) or strategic visions, which help to focus managerial attention and indicate which core capabilities the firm must develop further and how, so as to succeed in its chosen business segments (Schoemaker

1997:61). In general, scenario planning combines the following elements: environmental analysis; construction of scenarios and consistency check; implications for strategy; and strategy formulation and implementation. These elements appear in various ways and often much more detailed in scenario planning methodologies as presented by Mercer (1995), Postma and Liebl (2005), Warren (1995), and Schoemaker (1997).

The nature of scenarios. The question is whether scenarios are possible futures (Wilson 2000; cf. the understanding of scenarios in the UK FS exercises[4]) or forecasts of futures (Coates 2000). Scenarios can be considered a tool for anticipatory coordination where a scenario is understood as a forecast of the future – in which particular S&T are situated - will as it will most likely unfold (cf. Coates 2000). On the other hand, they can be used as a tool for articulation of possible futures, because future scenarios can be linked back to a choice of better action in the present – thus increasing the likelihood of a more positive scenario to come true (Wilson 2000). Traditionally, scenario planning has assumed the environment as given and independent of strategies responding to it. This view has now given way to one where there is a feedback link from strategy to environment, i.e. where the firm's responses to the emerging future can affect the environment (Warren 1995:11). This is in line with Godet's ideas about 'la prospective', where one future or another will be born out of the interaction between the various actors present and their plans (Godet 1989:48). La prospective refers to both a preactive (that is, be prepared for expected changes) and proactive approach (provoke desirable changes) to the future (Godet 2000:08; see also Godet 1989). In contrast, the 'Shell approach' emphasizes pre-activeness (and therefore selection of the best strategy). The 'Shell approach' has been much more pervasive then the 'prospective' approach of Godet (Postma and Liebl 2005:162-163). Chermack et al (2001) address theoretical underpinnings of the main elements of scenario planning. As far as we could discern, there is no link yet between empirical studies of technological disruption and the more theoretical literature on discontinuities. Cf. van Notten et al (2005) for a literature review of how discontinuity is addressed in futures literatures with a focus on scenarios.

Scenarios as tools for strategy development (including implementation). Some contributions in the innovation management and (really-) new product development literatures have bridged the gap between scenario planning and project management, by showing how scenarios can be used by researchers and technologists to inform decision-making ar project level.

In the more consultancy-style innovation management literature, Miller and Morris (1999) suggest using scenarios in the process of articulating future needs of customers. These scenarios describe how a technology can be used and what benefits may result.

In the NPD literature, Noori et al (1999a, b) have developed a scenario-based, so-called 'umbrella approach' to the assessment and management of breakthrough R&D projects, which involves a combination of scenario creation, back-casting, and environmental scanning/monitoring. Scenario creation comprises 'different worlds where, as a result of various sets of customer future requirements, alternative versions of the product being developed will be

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4 http://www.foresight.gov.uk/Previous_Rounds/Foresight_1994__1999/The_Use_Of_Scenarios_In_Foresight.html

successful' (Noori et al. 1999a:548). From these scenarios future customer requirements are derived, which lead to product sets. Back-casting will be used for determining how each future could evolve from and relate to the present, through a number of steps. These present-future pathways depend, to some degree, on factors over which the firm has no control. The back-casting should therefore constitute a strategic learning experience, helping managers 'to focus on a broader range of issues in the product development process' (Noori et al. 1999a:554-555). Project management needs to be accompanied by continuous monitoring of the general market and macro-environment in order to discover which of the forecasted futures is actually unfolding, and which of the pathways the project is following. It is crucial that it be coupled with a flexible product development process, which enables the firm to quickly respond to changes (Noori et al. 1999a:550).

Practicality issues. Scenario is very popular but difficult to implement. Scenario forecasting usually demands resources of a central planning staff and considerable investment of time; the forecasts must be genuinely useful and carefully balanced between stretching the imagination of management and being believable. Persuading line managers to make use of scenarios produced is a difficult part of the process (Mercer 1995). As the planning culture in most corporations is often biased toward single-point forecasting, the emphasis in scenarios on 'multipoint forecasting' is likely to cause confusion (Wilson 2000:24). Introduction of scenarios is a rather long term project (Mercer 1995:85-96; Shell Global Business Environment 2003:24). Harries (2003) in her literature review focuses on evaluation of scenario planning.

Tools for anticipatory coordination

Roadmapping

Roadmapping incremental innovation vs. roadmapping disruptive technologies. Roadmapping is a generic term that describes activities of the (usually iterative) articulation and specification of goals and the 'roads' to get there (Groenveld 1997). Roadmaps mostly articulate the futures of mature technological options, where products, product (or technology) drivers, and the regulation environment are known. There is by now a wealth of literature on roadmapping of incremental innovation (Albright and Kappel 2003; Barker and Smith 1995; Kappel 2001; Kostoff and Schaller 2001; McCarthy 2004; Phaal et al 2004; Probert and Radnor 2003; Rinne 2004). Roadmaps need to be maintained and updated to become effective. Where an actor to fulfill that function exists (in the case of the International Technology Roadmap for Semiconductors it is the International Sematech consortium), roadmaps become a powerful tool for creating alignment around technological and product options and to help accelerating their development. For this reason roadmapping is a promising tool for assessment of NES&T.

There have been attempts at modifying the existing techniques of roadmapping so as to be applicable to emerging, enabling technologies, both at industry and level and in science policy. Walsh (2004) reports how in a roadmapping exercise for top-down nanotechnology, certain requirements of traditional roadmapping approaches could not be met: definition of the scope and boundaries of the technology; specification of technology drivers and their targets; and identification of the product that would be the focus of the roadmap (Walsh 2004:170-172). Rather than considering the product-market paradigm, the author suggests using the technology product paradigm: a company uses a technology to form a 'core product', which is then used as a platform to derive application-specific products from.

Fiedeler et al (2004) and Fleischer et al (2004) suggest roadmapping as a tool for forecasting the way to possible future applications based on ongoing research or back-casting from envisioned products in order to set priorities for ongoing research. In both cases roadmapping is presented as an assessment tool to support policy formulation, i.e. to analyze whether possible applications 'are realistic and if the kind of nanoscience in mind is suitable for the realization of that application' (Fiedeler et al 2004). While Walsh's description of roadmapping enabling technologies reflects actual efforts, i.e. the International Industrial Microsystems and Top-Down Nanosystems Roadmap (IIMTDNR) developed by the international Micro and Nanotechnology Commercialization Education Foundation (MANCEF), the kinds of roadmaps suggested by Fiedeler et al (2004) and Fleischer et al (2004) have yet to be realized.

In strategic management of S&T we note Lizaso and Reger's (2004) approach at keeping roadmapping flexible, dependent on which future scenario unfolds. In contrast to many management papers they stress that managers have to understand the dynamics of technological innovation to be able to choose technologies of value for the organization long before the market introduction. Different directions of technological progress can make different scenarios happen. These can be anticipated and articulated using 'S&T knowledge'. Managers can identify identify the technologies that will constitute the possible futures, and their particular performance parameters. The approach results in a 'Technology Roadmap Architecture', comprising sets of market, product/service and process scenarios addressing particular questions (Lizaso and Reger 2004:74). Lichtenthaler's empirical studies of technology intelligence tools in MNCs have confirmed that roadmapping and scenarios are often coupled: separate roadmaps are developed for different scenarios (Lichtenthaler 2005).

Limitations. The main obstacles to conducting successful roadmapping exercises are often related to limited resources and the need to have various intra-firm units interacting. Customization of roadmapping techniques is one of the solutions suggested (Lee and Park 2005). Myers et al (2002) remain skeptical about how disruptive technologies could be forecast. Based on anecdotal evidence from a US case study on ion implantation, they find that a disruptive technology acquires maturity by moving through the three stages of proof of concept, establishment of a limited application, and widespread application. Because of the high risk of failing each transition, forecasting the next disruptive technology remains 'an elusive ambition' (Myers et al 2002:322-327; cf. also Kappel 2001:39).

Hype-cycles of emerging technologies

Underlying dynamics. The so-called 'hype-disappointment graph' has been used since 1995 by business consultants the Gartner Group as a tool for characterizing societal visibility of emerging technologies and aiding the decision-making in technology management processes. It captures hype and disappointment dynamics: The emergence of NES&T is characterized by increasing visibility for less or more distant outsiders in science, technology, policy-making, and society. While the reality of practitioners is characterized by uncertainty about the feasibility of options, and efforts at overcoming obstacles, the increasing visibility of new S&T leads in circles not involved in the development of the emerging science or technology to the rise of expectations and the creation of images of the science or technology, which are very remote from reality. This 'hype' is low on informative content, but directly states the relevance of the information to a social context (Guice 1999:85). It overplays expectations in the short term. The peak of inflated expectations is followed by a trough of disillusionment and declining interest of the remote groups. This disillusionment may eclipse the underlying longer-term value of the NES&T, and can even lead to decisions to withdraw funds for, and political support of, public research programmes (Brown 2003:7,9). As practitioners continue to work in public or private research labs or start-up companies, slowly shifting from exploration of the potential of the NES&T to exploitation of selected trajectories, the visibility of the science or technology undergoes qualitative changes. Wider awareness is now characterized by increasing realism.

The tool. Gartner monitors the development in emerging areas, and publishes comprehensive reports on their state. With respect to emerging technologies, Gartner chart technologies 'on the rise' (as diverse as Protein-DNA logic; Augmented Reality; and internet Wikipedias); 'at the peak' (micro fuel cells; speech recognition tools; Linux applications), 'sliding into the trough' (service-oriented architecture; smartphones; wi-fi hot sports); 'climbing the slope' (voice-over-internet protocol); and 'entering the plateau' (instant messaging). For Gartner, hype cycle monitoring is primarily an educational tool: Technologies should be adopted based on the individual needs and goals of each enterprise, not the generic levels of hype and disillusionment in the general marketplace.

Anticipated performance curves of disruptive technologies relative to performance as demanded by the market

The disruptiveness of new and emerging technologies. Scholars have produced a confusing number of concepts to describe effects of technological change and new technologies and innovations. Ehrnberg (1995) reviews the technological discontinuities literature (1970s-1990s) and highlights concepts used to describe discontinuities, such as 'radical innovation', 'technological discontinuities' (Anderson and Tushman 1990), 'technological paradigm shifts' (Dosi 1982), 'technological revolution', or 'technological breakthrough'. Garcia and Calantone (2002:117) identify in their study of NPD literature (1970s-2000) five approaches to categorizing innovation concepts. The most prominent one is the family of dichotomous categorizations, such as 'incremental vs. radical', 'routine vs. radical', 'incremental vs. breakthrough', 'continuous vs. discontinuous', or 'sustaining vs. disruptive'. NES&T are associated with breakthroughs, discontinuity, and disruptiveness. The 'breakthrough' concept implies a frontier, ceiling, or limit, which must be broken through. Moore's Law may be considered a vehicle that accelerates breakthrough R&D, as it predicts standards to be met by technology firms in the semiconductor sector at particular points in the future, on risking the danger of falling back in the competitive struggle. In the ITRS, which is guided by Moore's Law, breakthroughs of known material limits however appear in regular fashion, and do not seem to disrupt the field.[5] The sociology of S&T literature has contributed to an

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[5] In the case of the International Technology Roadmap for Semiconductors (ITRS) there is an additional driver: The ITRS uses as a reference an extrapolation of historical trends as guided by Moore's Law (Moore 1965; Schaller 1996;

understanding how scientific breakthroughs and technological innovations come about but has not contributed to assessment tools.

In the management and NPD literature, 'disruptive technology' and 'discontinuous innovation' are the most widespread terms used when assessing NES&T. 'Disruption' has the connotation of an external force, which intervenes in ongoing – by implication sustaining or incremental - processes. Where both technological competencies and market linkages are disrupted, one can speak of 'architectural innovation' as Abernathy and Clark (1985) have suggested. The popularity of the concept of disruptive technologies has been associated with Christensen's work since the mid-1990s. His contributions, which have been cited by scholars in the fields of NPD, marketing, strategy, management, and technology management (Danneels 2004), seem to have overshadowed earlier conceptualizations.

Disruptive technologies break through the usual product/technology capabilities and provide a basis for a new paradigm – discontinuous innovations (Kassicieh et al 2002; Kostoff et al 2004). Discontinuous innovation is 'the creation of a new line for business, both for the firm and for the marketplace' (McDermott and O'Connor 2002:425). For Rice et al (2002:332), an innovation is discontinuous in nature when it embodies new-to-the-world performances, with an at least five- to ten-fold improvement in known performance features, and yields at least a 30 per cent to 50 per cent cost reduction. These figures are not widely shared. Discussions at a more theoretical about discontinuities can be found in the forecasting literature (cf. Ayres 2000).

Using performance trajectories of disruptive technologies. Bower and Christensen (1995) introduce the concept of 'performance trajectories', which means the rate at which the performance of a product has improved, and is expected to improve, over time (Bower and Christensen 1995:45). 'Sustaining technologies' tend to maintain a rate of improvement. 'Disruptive technologies' at first often perform worse along one or two dimensions, and tend to be used and valued only in new markets or applications. Disruptive technologies can be strategically assessed via their anticipated performance trajectories, which start at a point below the trajectory of the market but soon break through from below, and raise the performance level (Bower and Christensen 1995:50). Technology and market needs trajectories often do not follow parallel paths: the technology performance trajectory rises more steeply than does the market needs trajectory. Presently underperforming technologies can thus meet market needs in the future (Christensen 1997).

Bower and Christensen (1995) suggest tools for spotting and cultivating disruptive technologies, including technology intelligence and monitoring activities. Their paper links up with the older literature on transition management from an old to a new technology base (cf. Keys 1997). Adner (2002) identifies demand conditions that enable disruptive dynamics, and suggests new indicators for assessing disruptive threats, as well as making ex ante distinctions between technologies that will become disruptive, and those that will remain inferior. Paap and Katz (2004) advocate the use of technology S-curves to predict the window when existing technologies will satisfy customers' expectations of performance.

Watson 1998; Scientific American 1997; Webopedia 1998; cf. Walsh et al 2005 on the ITRS, and Van Lente and Rip 1998 on mechanisms underlying the law).

Limitations. There is criticism of the disruptive technologies concept, too. Disruptive technologies are by their nature nascent and only can be revealed as being disruptive in hindsight (Kostoff et al. 2004). Mapping the trajectories of performance improvement demanded in the market vs. the performance improvement supplied by the technology is only straightforward for ex post case studies. Ex ante, one method would be extrapolating historical performance trends toward the future, which is difficult for young technologies (Danneels 2004:250, 251).

Comparison of learning curves of sustaining and disruptive technologies

Productivity increases with cumulative production or experience. The learning curves can be modeled and used to forecast productivity increases for similar technologies (Blancett 2002:58). Curves can be embedded in roadmaps, as in the case of Lucent Technologies' product-technology roadmap (Albright and Kappel 2003:34-36). Linton and Walsh (2004) develop a theory for modeling the learning curve for emerging process technologies (EPT). Their learning curves are characterized by both incremental and discontinuous improvements; the latter occur when current physical limits of the process are overcome, and lead onto a new learning representing the new constraining physical limit (until another jump occurs, and so on). Each new physical limit offers higher performances, also in relation to learning curves of existing, mature technologies. Using learning curves of existing, mature process technologies to forecast disruptive technologies would only lead to the incorrect assumption that physical limits will prevent further improvement (Linton and Walsh 2004:521; cf. also McDonald and Schrattenholzer 2002: 738).

Challenges. Learning curves are promising assessment tools of EPT provided the likely timing of the jump to a lower learning curve can be predicted. In the case of disruptive technologies, there is obviously little history, and slopes can only be extrapolated from a few data points (which might be affected by the typical changes in early market pricing strategy) (Albright and Kappel 2003:34, 36).

Forecasting

'Forecasting' is a generic term for a range of approaches and tools for the articulation of the future, often in order to develop business strategies for turbulent markets (Duus 1999; Makridakis 1996). Porter (1999) states that technology forecasting activity 'is dispersing under a variety of labels', such as 'competitive technological intelligence', 'technology foresight', or 'technology road mapping' (Porter 1999:26). Over the past ten years at least two literature reviews on forecasting tools have been published, covering subsequent periods in time: Winklhofer et al (1996), who cover the period 1973-1994, and Marino (2003), who reports on the period 1992-2001. Marino covers recent developments in environmental scanning, models, scenarios, Delphi, extrapolation, probabilistic forecasts, and technology measurement. In his paper Marino focuses on quantitative tools for forecasting, especially extrapolation, models, and probabilistic forecasts. This is why we decided not to cover technology forecasting in the stricter sense of the forecasting of a number of factors, while the 'softer' aspects of forecasting are dealt with in the foresight and scenario sections. From a bibliometric angle we note Porter's (1999) analysis of technology forecasting activity for the period 1986-98, which also includes a review of forecasting tools (creativity methods, monitoring, trend analysis, modeling, expert opinion, and scenarios).

Tools for portfolio and project management

Portfolio management

Definition. Cooper et al (2001) define portfolio management as the dynamic decision process of constantly updating and revising a business's list of active new product (and R&D) projects. The process entails comparative evaluation of new projects for selection and priority-setting (Cooper et al 2001:362). McDonough and Spital (2003) distinguish between 'portfolio selection' and 'portfolio management'. Portfolio selection (other terminology: 'R&D project selection', 'R&D resource allocation', or 'project prioritization') refers to the processes of comparative selection of a number of candidates for the project portfolio. Portfolio management is the actual, day-to-day management, including managerial decisions with respect to financial and human resources allocation. There is a body of literature on patent portfolios (cf. Ernst 1998), which we have not considered.

Portfolio management with front end of innovation projects. In the portfolio management literature we found a majority of empirical studies, most of them large-scale surveys (Cooper and Edgett 1997a and b; Cooper et al 1998, 1999, 2001). These empirical studies address issues such as initial project selection and portfolio effort, and based on their findings, often go on articulating best practice approaches. Method/model papers (Graves et al 2000; Spradlin and Kutuloski 1999) deal with improvements of portfolio techniques. The *Journal of Portfolio Management* offers a number of quantitative approaches and method papers but these are not really suitable for our purposes. A relatively recent special issue on portfolio management has appeared in *R&D Management* (2001) **31** (2). For front end of innovation projects (as distinct from incremental innovation projects), much of the information required to make project selection decisions is uncertain or even highly unreliable (Cooper and Edgett 1997a). In an R&D project portfolio matrix, which maps the strategic value of projects with respect to low/high customer benefit and low/high competitive advantage (cf. Mikkola 2001), most front-end-of-innovation projects would inhabit the low benefit/low advantage quadrant since at the beginning there is nothing but uncertain promises with respect to both criteria applied. What then would be the adequate criteria for selection of such high-risk projects with long development times? And what tools for monitoring project progress in the portfolio does the literature suggest?

The portfolio management literature treats the challenges that NES&T (or really new product development projects) present for portfolio building either only vaguely, or in a normative way, identifying project trajectories in terms of the matrix terminology (i.e., from a lower to a higher quadrant) without greater attention to evaluation criteria. McDonough and Spital (2003) found that 'more successful portfolios embrace risk, either in the market uncertainty or technical uncertainty dimension or both' (McDonough and Spital 2003:40). There is recognition of the challenges that the portfolio approach to high-risk projects presents: Projects are sometimes prevented from moving to a higher quadrant because ancillary innovations are not in place, such as market infrastructure and regulations, and as the technology is still at its infant stage, little is known regarding its life-cycle and high-volume costs (Mikkola 2001:431).

In the context of portfolio management we notice that in the strategic management literature, strategic R&D portfolio planning using business horizons has been suggested. These interlocking horizons extend into the long term future but while they are relevant for assessments of NES&T, the available literature often lacks really practicable tools, and there are also different opinions on how to define the horizons (cf. Szakonyi 1990; Baghai et al. 2000).

Flexibility-effectiveness tensions of NES&T. The literature on organizational learning has contributed some concepts to describe the essential strategic tensions of firms looking at NES&T, and tensions in the development of such new S&T. These tensions must be addressed in portfolio building when defining the nature of the balance between various projects. There are different ways of framing tensions in the innovation management and NPD literatures, such as the role and interrelationship of strategic flexibility vis-à-vis operational effectiveness (de Weerd-Nederhof and Gomes 2002) or competence building and leveraging (Sanchez 1997). Danneels (2002) has offered a competence-based product innovation typology. We refer to the seminal work of March (1991) on 'Exploration and exploitation in organizational learning' (article title). Exploitation means refinement and extension of existing competences, technologies, and paradigms, whereas exploration is experimentation with alternatives (March 1991:85). Any effort to improve organizational performance and strengthen competitive advantage involves trade-offs between exploration and exploitation. Translated into S&T terms, this trade-off has many dimensions. One is between (financial and organizational) investment in basic research on the one hand, and technological development on the other: Returns of exploitative activities are positive, proximate, and predictable, while returns on explorative activities are uncertain, distant, and often negative. March refers to the danger of path dependencies when saying that adaptive processes characteristically improve exploitation more rapidly than exploration, making them potentially self-destructive as the organization spends fewer resources on exploration (March 1991:73). A literature review on the use of the exploitation and exploration concepts in the innovation management literature has been published as a working paper by Li et al (2005).

Another trade-off is located in the development of the new S&T itself, the question when to switch from exploration of new facets to exploitation of some promising features. This issue is of interest in a number of literatures, including new business development, start-ups/spin-offs, and product platform development. Assessments are intrinsic to the formulation of the business model of spin-offs/start-ups but there does not appear to be a specific focus of the literature on assessment tools used.[6]

Product platforms based on emerging technologies. The product platform development literature discusses the advantages of using technology platforms for simultaneously entering a number of new markets. These studies are promising but have limitations, as we will show. Kim and Kogut (1996) study US semiconductor start-ups. In semiconductors, subfields have branched out, with some of them diverging (such as discrete/IC transistors), others converging (such discrete transistors and gallium arsenide devices into opto-electronics). The authors illustrate how firms have made decisions what new fields to move. Their point is about using technology trajectories for making

[6] Cf. some of the more recent, European studies on spin-offs, such as Benneworth 2001; Clarysse and Moray 2004; Clarysse et al 2005; Fontes 2005; Kaufmann and Tödtling 2001.

strategic decisions: 'Some technologies provide a starting point or platform for the exploration and development of new resources and have a high potential to spawn new markets. Other technologies are specific to certain applications and represent dead ends for further major development' (Kim and Kogut 1996:284). Current decisions with respect to entry and investment have an 'option' quality: entry in some markets will provide a firm with wider options than entry in other markets (Kim and Kogut 1996:293). As market opportunities are filled, the platform value of a technology diminishes. The goal is to develop the right platforms in order to participate, by a process of expansion and diversification, in the evolution of future opportunities (Kim and Kogut 1996:283). Kim and Kogut's findings are supported by the results of another long term study, Jones' (2003) study of firms and products in the telecommunications switching sector (PBX) finds that it is not only speed of development that impacts on a firm's competitiveness after radical technological change but also whether the firm has a platform strategy, as well as the rates of derivative introduction (Jones 2003:1265). The goal for managers should be to optimize an interdependent portfolio of projects as firms benefit from planned and coordinated family relationships among products (one design projects borrows from the other) (Jones 2003:1284). Other authors in the area of product platform development have offered a framework explaining the relevant product structure concepts that could be used to improve product strategies (Muffatto and Roveda 2002), or addressed planning and execution of different types of products within a product platform series (Tatikonda 1999).

Challenges. The challenge, however, is how to assess technologies in *real-time* in terms of such richness to spawn new markets. Kim and Kogut's (1996) study, for instance, is retrospective, and offers little in terms of assessment tools expect using expert opinion as input.

Project selection and evaluation tools

The literature. There is a very broad literature on project selection and evaluation, served by journals such as *European Management Journal*; *IEEE Transactions on Engineering Management*; *International Journal of Technology Management*; *Journal of Product Innovation Management*; *R&D Management*. Poh et al (2001) in their comparative study of a number of classes of R&D evaluation methods distinguish two families of R&D evaluation methods, 'Weighting and Ranking methods' (with scoring; AHP; and comparative methods); and 'Benefit-Contribution Methods' (with cost-benefit analysis; economic analysis; and decision-tree analysis) (Poh et al 2001:64). Coldrick et al (2005) stress that project selection models have to consider the different types of R&D: NPD projects would be valued using cost-benefit analysis, but existing product projects would be valued using discounted cash flow (DCF). The literature often addresses decision-making processes situated at managerial level, but where nevertheless R&D people have some input (Bordley 1998; Englund and Graham 1999; Jacob and Kwak 2003; Maylor 2001; Meade and Presley 2002; Ozer 1999; Poh et al 2001; Vislosky and Fischbeck 2000).

Options valuing. Managerial assessment techniques for R&D investment, such as discounted cash flow (DCF) or net present value (NPV), have been criticized as not suitable for R&D because they cannot deal with uncertainty; they are static decision processes, where future go/no go decisions are made with all currently available information and these decisions will not be revised when new information alters the value of the investment opportunity (Lint 2000:5-6). Real options theory (real R&D options; option management; options finance; valuation of technology) is considered an alternative to the above techniques; it has come into fashion over the past decade and is now used in general R&D planning, planning R&D in stages, testing, NPD timing, operations, abandonment, risk sharing, market funding, industry strategy, as well as regulations (Newton et al. 2004:114; Paxson 2001). Newton et al (2004) have recently provided a literature review on real R&D options, so we limit ourselves to some basics here.

The main premise in options valuing is that any existing R&D project implies an option of a follow-up project, which, given market growth, promises higher rates of return, and should therefore be implemented at the right time. Selection of projects is considered an act of identifying and exercising (call) options - contracts giving the option holder the right to buy something but not obliging him to do so. In terms of R&D projects, management, after initial investment in the project, may exercise the right to withdraw funds and stop the project on assessment of certain conditions. Technological uncertainty entails the promise of bigger profits, hence options valuing is presented as an assessment tool for 'risky' R&D projects (Perlitz et al. 1999). There are by now what could be termed hybrid approaches to real options – attempts at bridging the gap between the qualitative analytical approaches of strategic management and the quantitative valuation approaches of finance like those that have been offered by McGrath and MacMillan (2000) and Miller and Waller (2003). Newton et al (2004) suggest future research addresses modeling of the R&D in numerous stages, hence providing 'the R&D manager with milestones, or decision points where it can be decided whether it is worthwhile to invest further in the project' (Newton et al. 2004:126). While some companies undertake real options planning (cf. Lint [2000] for Philips Research), applications of options valuing often are simplified versions only, due to their mathematical complexity (Angelis 2000; Boer 2000; Lint and Pennings 2000; Perlitz et al. 1999). Still, even thinking in terms of options alone is a valuable tool (Doctor et al 2001: 83).

Challenges. We note that empirical studies of the use of project selection and evaluation tools have drawn rather contradicting lessons. On the one hand, there is the tendency to call for tools that are more practical, and can be successfully deployed when there is limited time. On the other hand, other authors state that existing tools and methods lack a scientific grounding and are simplified versions of older approaches such as GANTT, and, against the lack of academic interest in fields such as project management, call for the broadening of the disciplines that could contribute to sound tools development. We see this as a sign of tensions that characterize assessment tools, i.e. the tensions between the quality of the tools, and their tendency to introduce transparency into the assessment process, and the influence of the context on the choice of tools and on the assessments.

Tools for managing front-end innovation processes in NPD

Terminology and literature. One of the questions that the literature on the front end in NPD addresses is to what extent can techniques from incremental innovation projects (versions of cross-functional stage-gate approaches, such as stage-gate; facilitated stage-gate; 3rd generation stage-gate including fuzzy and flexible gates; cf. Griffin 1997) be used to manage radical innovation projects? Some authors discuss the 'fuzzy front end' as distinct from NPD. Others make a similar distinction but prefer the 'really new product development' phrase. With respect to technology/product terminology, there are concepts such as really new/breakthrough/revolutionary/pioneering products, as well as radical or discontinuous innovations (Bayus et al 1998:108). In this paper we follow Koen et al.

(2001), who differ between activities that characterize the 'front end of innovation', and NPD activities. Both are distinct but the former do sooner or later morph into the latter.

Empirical studies of the front end of innovation tend to fall in one of the following three categories: (1) retrospective, long term studies (such as Wood and Brown 1998 on the commercialization of laser diodes at Sony); (2) ongoing, mid to long term studies (such as McDermott and O'Connor 2002; O'Connor 1998; O'Connor and Veryzer 2001; O'Connor and McDermott 2004; O'Connor and Ayers 2005; Rice et al 1998; and Rice et al 2002); and (3) one-off surveys (Karlsson and Åhlstrom 1997). Many of the contributions presented here have been published in the *Journal of Product Innovation Management*; note the special issue in (1998) **15** (2).

Tools. Front end processes are modeled as iterative steps of the funneling of opportunities and ideas into project activities (Koen et al 2001; Lichtenthaler et al 2004; Rice et al. 1998; Song and Montoya-Weiss 1998; Veryzer 1998b). Managerial techniques often initiate and support communication either among project team members, or within the company environment driving the funneling activities. Traditional quantitative market-research techniques cannot be applied and assessments of market potential, size, and growth are not an issue (O'Connor 1998; Veryzer 1998a). The tools that can be used with some benefit are those that aid market visioning (O'Connor and Veryzer 2001), which will in turn aid the technological design and development activities, but also comparative selection between a number of promising candidates (O'Connor and Ayers 2005:25). Another body of literature is concerned with the later stages of radical innovation projects, i.e. transition management from project to commercialization (Rice et al 2002).

Empirical studies highlight two important kinds of relationships, firstly between tools and organizational context; sceondly, between personal skills that are relevant for management and assessment tasks, and formalized tools that could support these tasks:

- Lichtenthaler et al.'s (2004) study implies that the organizational environment has an influence on the degree to which assessments are formalized. They highlight 'process-oriented companies', which show a high degree of formalization of the early innovation phases, and where there is pronounced interaction between the management of radical innovation process and the process of strategy planning (Lichtenthaler et al 2004:105-106). In these process-oriented companies, technology and market intelligence (which inform the funneling sequences of radical innovation projects) are undertaken more systematically than in other companies where the innovation process is less formalized (Lichtenthaler et al 2004:107).
- Reid and de Brentani (2004) stress that personal communicative skills of a champion, rather than the application of formalized tools, decide on whether an idea can be successfully pushed or not (Reid and de Brentani 2004:177). McDermott and O'Connor (2002) stress similar skills of negotiation, handling ambiguity, setting a course of action amid skepticism, and managing boundaries between the project team and outsiders, such as senior (McDermott and O'Connor 2002:434). We note, but do not discuss, some of the more theoretical sociological studies of decision-making processes in technological innovation: These have undermined the validity of rational actor/choice models, according to which decision-makers, when selecting projects, strive to reach the best possible conclusion by a process free from the subjective social distortions emerging from conflicting interests. Part of this process is the use of decision-support tools (cf. Cabral-Cardoso 1996:50), which often are used to legitimize decisions taken prior to application of the tools.

Summary of the findings and research gaps

In this last section we first highlight the main findings of our paper, with respect to the tools categories as well as some generalizable lessons on requirements for the better functioning of tools. Some of the findings imply research gaps, and we point out a few possible, promising ways how to close them.

Anticipatory tools

- *Foresight* has started making greater use of tools that allow for articulation of multiple futures, such as scenario building.
- *Bibliometrics* show an intrinsic, retrospective bias. Insights into science-technology relationships are necessary, in addition to bibliometrical skills, to make proper use of bibliometrics as an anticipatory tool.
- *Scenarios* can be considered a tool for anticipatory coordination where a scenario is understood as a forecast of the future – in which particular S&T are situated - will as it will most likely unfold. On the other hand, they can be used as a tool for articulation of possible futures, because future scenarios can be linked back to a choice in the present of better action – thus increasing the likelihood of a more positive scenario to come true. However, complex techniques, or tools which produce ambiguous results that are difficult to operationalize (as brought about by the emphasis scenarios in on 'multipoint forecasting'), are difficult to use.

Tools for anticipatory coordination

- There have been attempts at modifying *roadmapping techniques for forecasting disruptive technologies*, while similar approaches have been suggested for drawing up strategic research agendas in nanoscience. However, there is skepticism about forecasting discontinuities.
- Using *hype-cycles* of emerging technologies as investment decision aids strikes us as an interesting approach because the influence of dynamics in the environment of NES&T on these is assessed, rather than extrapolating future applications from the top of the hype.
- *Mapping the trajectories of performance improvement demanded in the market vs. the performance improvement supplied by the technology* is only straightforward for ex post case studies. Ex ante, one method would be extrapolating historical performance trends toward the future, which is difficult for young technologies. For learning curves there is the challenge of modeling the likely timing of the jump to a lower curve. In the case of disruptive technologies, there is obviously little history, and slopes can only be extrapolated from a few data points (which might be affected by the typical changes in early market pricing strategy).

Tools used in portfolio and project management

- The *portfolio management* literature treats the challenges that NES&T (or really new product development projects) present for portfolio building either only vaguely, or in a normative way, i.e. not going beyond stating that radical projects have to be moved from lower to higher quadrants.
- For *front end of innovation projects*, much of the information required to make project selection decisions is uncertain or even highly unreliable. For the management of front-end innovation processes in NPD, traditional quantitative market-research techniques cannot be applied. Tools that can be used with some benefit are less quantitative in nature, such as those that aid market visioning.
- The literature on *organizational learning* has contributed the concepts to describe the essential strategic tensions of firms looking at NES&T, and tensions in the development of such S&T. Any effort to improve organizational performance and strengthen competitive advantage involves trade-offs between exploration and exploitation. Another trade-off is located in the development of the NES&T itself, the question when to switch from exploration of new facets to exploitation of some promising features. This issue is of interest in a number of literatures, for instance *product platform development*. Product platforms can be used for simultaneously entering a number of new markets. Only the right platforms can undergo subsequent expansion and diversification but the challenge is how to assess technologies in *real-time* in terms of such richness to spawn new markets.

Requirements for the better functioning of tools

Another result of the literature review is consolidation of insights into the conditions that must be satisfied, or the factors that need to be recognized, for tools to be applied usefully in assessment/technology intelligence activities. In the following we refer to results from empirical studies in companies, which we think are valid across a spectrum of organizations:

- **Need for practicality**. In many studies with an empirical background authors have reported on practitioners' problems with the practicality of available tools. Complex and sophisticated tools stand a lesser chance at being used properly, or adopted on a larger scale. Lichtenthaler (2005) finds that simulations, patent analyses and bibliometrics are so complex that they were only used by experts. Companies assess the strategic importance of an issue and select complex methods only for the most important issues. Kostoff and Geisler (1999) note when describing a prototype textual data mining implementation program conducted in 1998 at the US Office of Naval Research that 'many of the papers in the management science literature are very sophisticated, while most of the techniques actually used by practitioners are very primitive' (1999:497).
- **Flexibility to enable local adaptations**. Many of the existing technology intelligence tools are suited for large R&D departments. SMEs have limited knowledge, human and financial resources and need special tools. In addition, many strategic tools designed to aid strategic planning and decision-making are not sufficiently technology-related (Savioz and Blum 2002:91); they often are built far away from the intra-firm arenas of business decision makers (Duus 1999:175). For a number of organizations where tools such as scenario planning and technology foresight are being used, authors have found adaptations of the tools to the specific needs of the organization or the time and personnel resources at its disposal.
- **The fact of complementary and ex-post use of tools**. Lichtenthaler (2005) finds that assessments can be supported by tools but not completely substituted by them (Lichtenthaler 2005:393). Hence we can speak of

complementarities of the use of explicit tools and personalized assessment skills. Furthermore, selection of technology intelligence tools is not always based on rational choice, and tool-based analyses can be used for ex-post rationalization of decisions taken earlier (Lichtenthaler 2005:390).

- **Fuzzy boundaries of tools and evaluation problems**. It often is not very clear what actually counts as tool, where the boundaries are with 'techniques', 'methods', 'systems', 'procedures', or 'methodologies' (cf. Brady et al 1997; Hussey 1997; Matzler et al 2005; Rigby 2001; Rigby and Gillies 2000). Reger finds with respect to technology foresight that the process is not very structured (2001:536-537). The epistemological and science studies literature, as well as the more empirical management literature have discussed this issue but there is still no generally shared understanding. This problem has implications for the evaluation of assessment tools: what is more important, the quality of the tools or the organizational context, including the capabilities of the staff involved in assessment/TI activities?
- **Communicative dimension of tools**. Several authors stress that assessment tools comprise a communicative function, which is instrumental in bringing different sets of people together. Cooper and Edgett (1997a), with respect to the use of bubble diagrams in portfolio management, state that 'these methods are information display, not decision models per se. […] these charts and maps are only a starting point for discussion. Management still has to translate the data into prioritization decisions' (Cooper and Edgett 1997a). However, the benefits of communication within and across units will not always be fully realized. There are also *bottom-up/top-down tensions in assessments* between researchers/technologists and managers. McDonough and Spital (2003) found in their study of portfolio management practices evidence that where R&D personnel were given some percentage of their time to be creative and inventive, they came back with a number of projects that flooded the portfolio. These researchers and engineers would not see the 'ramifications of downstream problems' (McDonough and Spital 2003:41), i.e. further efforts necessary to lead the project into development, scaling up, and commercialization phases. Thus a lot of personnel are stretched across too many projects. Top-down dynamics have in fact been stressed in the strategic management literature. Most of the tools in the strategic management literature are developed for strategic decision making of a firm or a unit within a firm and NES&T is one aspect that the tool has to take into account. Strategic R&D management is conceptualized as integration of R&D activities into a company's technology and business strategy (Roussel et al. 1991:17). The assumption here is that by working out 'ex ante plans for better ways of dealing with potentially favorable and unfavorable events before they actually occur', threats can be minimized, opportunities optimized, and the company's future outlook improved (Madsen and Ulhøi 1992:312). The 'piecemeal and bottoms-up approach for generating R&D proposals' (Szakonyi 1990:393) has to be replaced by a strategic company perspective. Inputs from the various functions and decision-making instances of the company (corporate/divisional R&D only being one of them) will result in an integrated corporate/business/R&D strategic plan (Roussel et al. 1991:04). In other words, R&D managers are expected to apply selection criteria consistent with strategic considerations at company level to R&D portfolio building (Szakonyi 1990:393).

Research gaps

Lack of tools for assessments of open-ended developments in science. The majority of the tools reviewed here, while widely known, is used by technologists, personnel with a strategic management role in companies, and also policy makers. The impression from the literature is that there are fewer tools used for assessments of open-ended developments in science, at the level of research groups. To check this impression we undertook, on completion of the literature scan for the period 1995-2004, a long-term scan of two key journals, *Research Policy* and *Technology Analysis and Strategic Management*. We studied issues from the fifteen-year period 1989-2004 (the first volume of *TASM* was published in 1989) but found almost no relevant contributions.

Would this be a gap that scholars should address? There is no simple answer to this question. Scientists do undertake assessments all the time but implicitly so, i.e. they have a set of skills or personalized assessment techniques that, while communicable, have not been codified. In part these skills are related to their being at the research front of a scientific field, which entails continuous monitoring what is going on in the field, and based on the observations making decisions what direction to continue with, or whether to move elsewhere in order to stay innovative. These assessments are functioning. In addition, there is commonly resistance from many researchers against the linearity bias that assessment tools, such as roadmapping, introduce to their research activities; there is the perceived threat of stifling creativity. However, with researchers being involved in evaluation of public programmes and project proposals and strategic agenda setting for public organizations (cf. NIH) and R&D programmes and technology platforms, with the growing expectations in the strategic science paradigm of valorization of high investments in research areas, but also the growing pressure on public institutions and programmes to introduce transparency in their decision making processes, assessment tools are becoming more important. The uptake of foresight, and to some extent roadmapping (at institutional level) in the public sector, is an example that this need is realized.

Suggestions. We advocate further research on assessment tools for science. In line with the findings on requirements for the better functioning of tools we assume that (1) these tools will always be combined with non-explicit forms of intelligence, such as 'gut feeling' about something (subjectively aggregated from long term experience of the working environment), and (2) they must be practical. We suggest future research focus on two important aspects: (a) the role of emerging linkages for the success of the science or technology in question, and (b) dynamics in the wider environment, which might conspire for or against the science or technology, i.e. hype-disappointment dynamics. Corresponding tools could look like this:

- **Tools to assess richness of emerging linkages**. NES&T are characterized by trade-offs between costly and time-consuming exploration (but with the benefit of exploring a number of potentially useable ideas) vs. quick exploitation – and with the disadvantage of having only a small technology base explored. At the level of NES&T these trade-offs are intrinsic to any new development. They cannot be resolved as such, but practitioners, when in the process of making decisions whether to switch to exploitation, or which technological paths to select, can benefit from the broader range of assessment criteria. This means that NES&T can be assessed in terms of the number of linkages across scientific and technological fields they promise: the higher the number, the higher the probability that the richness of NES&T will be exploited in some or other way. Here we could think of comparative assessments undertaken at the level of public R&D programmes. Georghiou and Roessner (2000) have noted similar approaches to evaluating basic science programmes, i.e. those emphasizing evaluation in terms of the creation of linkages between various actors. There is Bozeman and Roger's work from the 1990s, who propose a 'pre-economic approach' to evaluating scientific knowledge, based on the range and repetition of uses of new knowledge both by scientific colleagues and by technologists. These exchanges are embedded in new collective arrangements, which often follow innovations. Bozeman and Rogers' ideas link up with the thrust of the work at the Centre for Sociology of Innovation (CSI) in France, where emphasis of evaluation is placed on networks assembled to realize innovation in collective goods; cf. Callon et al (1991). The challenge is to have - for both project coordinators and programme panelists - a reliable, real-time tool for mapping and assessing these linkages. Such tools would have to be continuously deployed; there cannot be initial (one-off) assessments only. The main task is to try and steer the creation of such emerging linkages in two directions, i.e. one fostering continuing exploration of the scientific and technological facets of the NES&T, and one, which is more application oriented. Ongoing assessments would also enable integrating ELSA components in such a way that they are not add-ons but lead to societally robust and acceptable development of the NES&T.

- **Tools for mapping hype-disappointment patterns in order to articulate strategy**. 'Hype-disappointment cycles' (HDC) are at the core of the Gartner Group's hype-disappointment graphs. We suggest developing a tool based on cyclical dynamics in new areas of science. Scientific research areas have their growth and decline cycle, as has been documented in the sociology of science, and promise can shade into hype. Fields with low entrance thresholds are especially affected by hype-disappointment dynamics as it is comparatively easier for new entrants to move into, and exit, the field. Cyclic patterns allow for articulation of two strategies with different sets of benefits: moving into the field before the hype (hoping to contribute to path creation), or after the disillusionment (with the benefit of being able to select between more clearly articulated paths). The HDC can be used as a tool for observation of these patterns of expectation, and to aid decision making. Fields with high entrance thresholds are presumably less affected by hype-disappointment dynamics (even if there are exceptions, as in those parts of nanoscience and nanotechnology which need expensive infrastructure).

Assessment of NES&T in terms of strategic impacts, such as the potential to "break through" recognized frontiers, ceilings, or limits, or "disrupt" existing technology-product linkages (Kassicieh et al 2002; Kostoff et al 2004; Walsh 2004), certainly is a way of pushing for exploitation of NES&T. But their benefits can materialize in a number of fields quite different from where they emerged; these are fields, which any linear projection into the future of present promises of NES&T would certainly fail to locate. Indeed, studies of NES&T have over the past decade emphasized non-linearity of innovation and dynamics of technological change (cf. Rip 1995:418-421). Clearly, there is no prospect of a 'manual' how to assess new and emerging, possibly breakthrough science and technology. Given the differences between scientific and technological fields and their dynamics, it is not clear how general such assessment approaches and tools could be. But we hold that the most important feature of NES&T is that they are characterized by *richness* of possible applications. Any selection of options thus is embedded in the search process, and its assessment and management, to which tools must speak. This is the main lesson for researchers, technologists, research managers, and S&T policy makers.

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