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Technology futures analysis: Toward integration of the field and new methods

Technology Futures Analysis Methods Working Group*

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Abstract

Many forms of analyzing future technology and its consequences coexist, for example, technology intelligence, forecasting, roadmapping, assessment, and foresight. All of these techniques fit into a field we call technology futures analysis (TFA). These methods have matured rather separately, with little interchange and sharing of information on methods and processes. There is a range of experience in the use of all of these, but changes in the technologies in which these methods are used—from industrial to information and molecular—make it necessary to reconsider the TFA methods. New methods need to be explored to take advantage of information resources and new approaches to complex systems. Examination of the processes sheds light on ways to improve the usefulness of TFA to a variety of potential users, from corporate managers to national policy makers. Sharing perspectives among the several TFA forms and introducing new approaches from other fields should advance TFA methods and processes to better inform technology management as well as science and research policy.

Keywords: Technology futures analysis; Forecasting; Research and development

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1. Introduction

Analyses of emerging technologies and their implications are vital to today's economies, societies, and companies. Such analyses inform critical choices ranging from the multinational level (e.g., the European Union) to the individual organization (e.g., a company). Decisions that need to be well-informed concern setting priorities for research and development (R&D) efforts, understanding and managing the risks of technological innovation, exploiting intellectual property, and enhancing technological competitiveness of products, processes, and services.

There are many overlapping forms of forecasting technology developments and their impacts, including technology intelligence, forecasting, roadmapping, assessment, and foresight. There has been little systematic attention to conceptual development of the field as a whole, isolated but uncoordinated research on improving methods, selection of methods, or integration of analysis and stakeholder engagement. This collectively authored paper seeks to lay a framework from which to advance the processes to conduct and the methods used in technology futures analysis (TFA).

2. Our framework

To integrate the wide variety of technology-oriented forecasting methods and practices, we introduce an umbrella concept—TFA. TFA represents any systematic process to produce judgments about emerging technology characteristics, development pathways, and potential

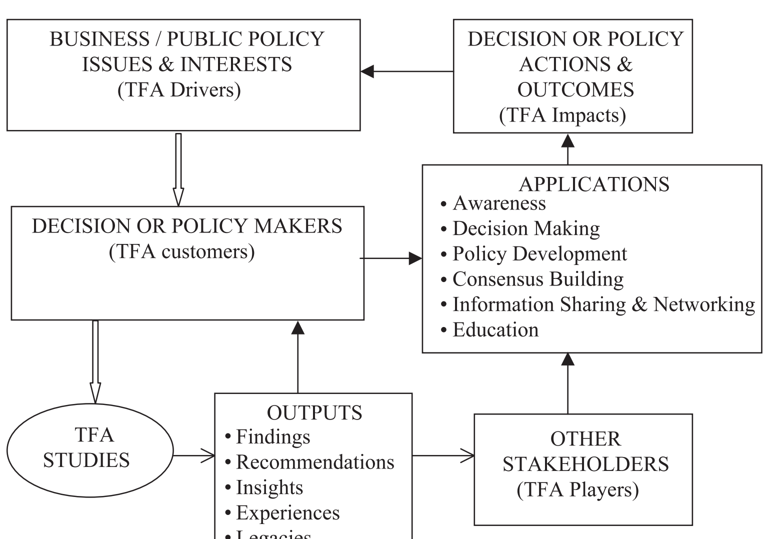

Fig. 1. A framework for TFA.

impacts of a technology in the future. In this sense, TFA encompasses the broad technology foresight and assessment studies of the public sector and the technology forecasting and intelligence studies in private industry. "Technology foresight" refers to a systematic process to identify future technology developments and their interactions with society and the environment for the purpose of guiding actions designed to produce a more desirable future. "Technology forecasting" is the systematic process of describing the emergence, performance, features, or impacts of a technology at some time in the future. "Technology assessment" is concerned with the impacts of technology.

Our view of the strategic components of TFA appears in Fig. 1, which shows a structured framework of the major forces and elements affecting the TFA process and arising from TFA activities.

3. Analysis: TFA methods

Table 1 presents a compilation of many of the methods of TFA. A primary reference is the CD-ROM *Futures Research Methodology, Version 2.0*, edited by Glenn and Gordon [1]. In the table, based on Ref. [1, chap. 27], the second column offers our classification of the individual methods into nine "families" of methods. Note that some methods compile information; others seek to understand interactions among events, trends, and actions. Some are definitive while others address uncertainty (that is, they involve probabilistic analysis). These tend to differ in approach and skills required. The third column offers our judgment as to whether the method is mainly "hard" (quantitative: empirical, numerical) or "soft" (qualitative: judgmentally based, reflecting tacit knowledge), and whether it is normative (beginning the process with a perceived future need) or exploratory (beginning the process with extrapolation of current technological capabilities). The last column gives some references that can serve as a starting point for obtaining more details. In addition to the listed TFA methods, one might include other techniques, for instance:

- Benchmarking (comparative representations using various methods' outputs
- Information visualization approaches (mapping, interactive graphical representations)

A word about models is in order. Linstone [31] distinguishes two functions of the models:

(a) the ability to draw real-world predictions from an abstract mathematical model, and
(b) an abstract-thinking aid, revealing or illuminating some aspect of system behavior in a simple way or unlocking an insight.

In case (b), we harbor no illusion that the model represents the system realistically; we use the model as a key to discover a new insight or point to a hidden link. Role (b) makes modeling an exceedingly valuable learning tool, but it is role (a) that has led us so frequently astray.

Table 1
TFA methods

Method [and variations]	Family	Hard or soft	Exploratory or normative	Reference
Action [options] analysis	V	S	N/Ex	
Agent modeling	M&S	H	Ex	[1, chap. 21,2–4]
Analogies	Desc	H/S	Ex	[5]
Analytical hierarchy process (AHP)	V	H	N	[6]
Backcasting	Desc	S	N	
Bibliometrics [research profiling; patent analysis, text mining]	Mon/Stat	H/S	Ex	[1, chap. 20,7]
Brainstorming [brainwriting; nominal group process (NGP)]	Cr	S	N/Ex	
Causal models	M&S	H	Ex	[8]
Checklists for impact identification	Desc	S	Ex	
Complex adaptive system modeling (CAS) [Chaos]	M&S	H	Ex	[9–11]
Correlation analysis	Stat	H	Ex	[8]
Cost–benefit analysis [monetized and other]	V	H	Ex	[12]
Creativity workshops [future workshops]	Cr	S	Ex/N	[13]
Cross-impact analysis	M&S/Stat	H/S	Ex	[1, chap. 6,14]
Decision analysis [utility analyses]	V	S	N/Ex	[15]
Delphi (iterative survey)	ExOp	S	N/Ex	[1, chap. 3,16]
Demographics	Stat	H	Ex	
Diffusion modeling	M&S	H	Ex	[17]
Economic base modeling [input–output analysis]	M&S/V	H	Ex	[18]
Field anomaly relaxation method (FAR)	Sc	S	Ex/N	[1, chap. 19,19]
Focus groups [panels; workshops]	ExOp	S	N/Ex	[1, chap. 14]
Innovation system modeling	Desc	S	Ex	[20–22]
Interviews	ExOp	S	N/Ex	
Institutional analysis	Desc	S	Ex	[14]
Long wave analysis	Tr	H	Ex	[23,24]
Mitigation analyses	Desc	S	N	
Monitoring [environmental scanning, technology watch]	Mon	S	Ex	[1, chap. 2,25–27]
Morphological analysis	Desc	S	N/Ex	[28,29]
Multicriteria decision analyses [data envelopment analysis (DEA)]		H	N	[30]
Multiple perspectives assessment	Desc	S	N/Ex	[1, chap. 24,31]
Organizational analysis	Desc	S	Ex	
Participatory techniques	ExOp	S	N	[1, chap. 14,32,33]
Precursor analysis	Tr	H	Ex	[8]
Relevance trees [futures wheel]	Desc/V	S	N/Ex	[1, chap. 12,34]
Requirements analysis [needs analysis, attribute X technology matrix]	Desc/V	S/H	N	
Risk analysis	Desc/Stat	H/S	N/Ex	[35,36]
Roadmapping [product-technology roadmapping]	Desc	H/S	N/Ex	[37–41]
Scenarios [scenarios with consistency checks; scenario management]	Sc	H/S	N/Ex	[1, chap. 13,42–44]

Table 1 (*continued*)

Method [and variations]	Family	Hard or soft	Exploratory or normative	Reference
Scenario-simulation [gaming; interactive scenarios]	Sc/M&S	S	N/Ex	[45]
Science fiction analysis	Cr	S	N	[46]
Social impact assessment [socioeconomic impact assessment]	Desc	S	N/Ex	[47]
Stakeholder analysis [policy capture, assumptional analysis]	Desc/V	S	N	[48,49]
State of the future index (SOFI)	Desc	H/S	N/Ex	[50]
Sustainability analysis [life cycle analysis]	Desc/M&S	H	Ex	[51]
Systems simulation [system dynamics, KSIM]	M&S	H	Ex	[1, chap. 15,52–54]
Technological substitution	M&S	H	Ex	[55–57]
Technology assessment	Desc, M&S	H/S	Ex	[14]
Trend extrapolation [growth curve fitting and projection]	Tr	H	Ex	[8,58–60]
Trend impact analysis	Tr/Stat	H	N/Ex	[1, chap. 5]
TRIZ	Cr	H	N/Ex	[61–63]
Vision generation	Cr	S	N/Ex	

"Family" Codes: Cr = creativity; Desc = descriptive and matrices; Stat = statistical; ExOp = expert opinion; Mon = monitoring and intelligence; M&S = modeling and simulation; Sc = scenarios; Tr = trend analyses; V = valuing/decision/economic.
Codes: H = hard (quantitative); S = soft (qualitative); Ex = exploratory; N = normative.

We note some key points and recommendations:

1. TFA does have some standard practices and common features despite the broad menu of methods.
2. Most TFA work warrants use of multiple methods, both quantitative and qualitative. These ought to complement each other, striving to compensate to the extent possible for weaknesses in any one approach. The choice of methods is inevitably affected by data availability.
3. Expert opinion methods are limited by what people perceive as feasible, colored by their shared beliefs and their limited imagination, for example, inability to conceive of many surprises. Example of limited imagination: wireless voice communication was not envisioned even shortly before it became a reality. Example of soaring imagination: prediction of birth control before it became available or submarines and space travel (in science fiction).
4. Many models assume linear relationships among variables, ignoring multivariate interactions and resulting nonlinearities.
5. The time horizon strongly affects methodological appropriateness—extrapolative approaches are usually suitable only for shorter terms. There are inherent limits to the ability to forecast the behavior of complex adaptive systems; they are characterized by domains of chaos and by high sensitivity to initial values. Uncertainty and surprises mount as we probe further into the future. Therefore, robust strategies are sought that are

suitable over a wide spectrum of scenarios and point to actions that increase the likelihood of desired future states while permitting adaptation over time as more information becomes available and uncertainties are resolved.

6. TFA studies aspire to generate reproducible results by spelling out "how" outcomes have been arrived at.
7. Assumptions must be made explicit regarding conceptual constructs, data quality and comprehensiveness, and methods being applied. Assumptional analysis may be useful to bring to the surface the beliefs held by each stakeholder about the assumptions being made by other stakeholders, a situation that often breeds misunderstanding [31].
8. Scale matters. There is a contrast between agent modeling that focuses on individuals' choices and systems modeling. Impact assessment varies greatly between localized analyses that draw upon primary data (e.g., personal interviews) and regional or national or global analyses that must rely upon secondary data (e.g., compilations by others, demographics, and epidemiology). Study resources, time available, and user preferences influence the choice of methods.
9. Despite the focus on technology, TFA requires treatment of important contextual influences on technological development and, conversely, the impact of technological development on the socioeconomic context.
10. TFAs should aim to be useful. To this end, a later section addresses the interplay between product and process considerations.

4. Process—the conduct of TFA

In TFA, the process is vital to facilitate its acceptance and use by the client and stakeholders. For example, the use of foresight processes to engage previously uninvolved players may hold a higher priority than technology information products themselves.

Multiactor considerations are central to much TFA. Decision making in a multiactor context takes place in a network where actors interact and each attempt to get the best outcome from his/her unique perspective. Consider four types of process:

1. Participative approaches. Basic idea: by involving stakeholders and others in the analytic processes, (a) some of the key behavioral elements are included; (b) the variety of inputs and thereby the quality of results will increase (in terms of richness of viewpoints, taking the expertise of stakeholders into account); (c) it will lead to broader support for the results; and (d) it may contribute to the democratic character of the process.
2. Process management. This is an approach that has originated from policy network theory [64]. The basic notion is that well thought out 'conditions and rules of the game' are needed to enhance the probability of progress in complex, multiactor situations.
3. Negotiation-oriented approaches. In this case, analytic efforts are primarily oriented to exploring possible compromises, finding solutions in which the interests of key stakeholders are intertwined.

4. Argumentative approaches [65]. In this line of thinking (also known as the dialectic approach), the focus of analysis and debate is on the argumentations (or perceptions) of stakeholders instead of on ‘objective’ facts.

5. Analysis and process together: scoping and framing the TFA

The scope of a technology forecasting, foresight, or impact study can loosely be defined as the ‘application area’ for TFA. Scoping lays out the playing field of the activity where the study applies at what level of detail and which issues are central. Therefore, the scope of a TFA gives information about the structure of the content. For instance, three elements of scope for the famous future study ‘The Limits to Growth’ are as follows: a computer simulation model (‘World 3’), the world (geography), and the time horizon (2100) [53].

Secondly, scoping should consider the process by which the study is carried out [66,67]—i.e., the actions to be taken in performing a TFA (the ‘how’ to do it). To describe the process, we need a ‘model’ or framework of the way TFA is carried out. There are a few of these frameworks, for instance the process structure of foresight has been divided into three phases of input, foresight (or throughput), and output and action [68,69].

The scope has to do with all three phases. It can refer to the content of a future study (themes and methodology applied) and to the elements that make up the process (management, participants, etc.) of a study. But one has to be aware that in modern, more continuous foresight activities, this differentiation of the three phases cannot easily be made. The German Futur, for example, runs different themes in all phases at the same time [70].

The question of how scope issues affect TFA is indeed important but can also be turned the other way round: How do the TFA methods affect the scope of the future study? That is, if objectives or a method are chosen, some scope issues are necessarily predetermined. For instance, if someone makes use of a Gompertz curve to predict the future course of a certain variable, the choice of the time horizon (a scope issue) is limited, at least if he or she wants to make a plausible prediction. But to address the initial question, for making an operational decision (for instance whether to make a certain specific investment in a target technology), which is a scope issue, an exploratory method such as visioning is not suitable because it does not give detailed enough information to support a specific decision.

That means that scope issues and the choice of TFA methods influence each other. The scope of the study can, for instance, limit the type of methods that are suitable, and a certain TFA method can limit the time horizon or other scope elements (e.g., breadth, communication). Our next step is to work out these relationships in more detail.

The scope issues of a TFA are twofold: (1) issues related to the content of the activity and (2) issues relevant to the performance (processing) and organization of the TFA activity (process). Table 2 lists scope issues. Note how issues and implications interact quite heavily with each other.

We have noted the desirability of applying multiple methods [71]. Now we consider deliberately striving to take into account technical, organizational, and personal perspectives [31]. Each perspective yields insights not attainable with the others. The technical perspective

Table 2
TFA content and process scoping issues

Scoping issue	Some implications
Content issues	
Time horizon	data needed, suitable methods
Geographical extent	data (proximity affects direct vs. secondary access)
Level of detail micro (company), meso (sector), macro (national, global)	process—nature of interaction with stakeholders
Process issues	
Participants (number, nature—experts or broader, disciplinary mix)	how expertise is tapped, how study is conducted
Decision processes (operational, strategic, visionary)	choice of experts
Study duration (minutes to years)	methods usable
Resources available (funding, data, skills)	methods suitable; modes of access to expertise
Methods used	data needed, analytical outputs
Organization	methods suitable, staffing, process management
Communication flows (internal, external)	process management, nature of participation
Representation of findings (technology information products)	usability by various audiences

(T) contributes problem-solving expertise and tangible products to the TFA, favoring methods such as analytical modeling. The organizational perspective (O) recognizes the importance of organizational and institutional roles in shaping technological innovation and its diffusion. What would it take to attain adoption of the target innovation by various stakeholders? The personal perspective (P) picks up the importance of strategic leadership, product championing, and other individual considerations affecting successful innovation. In our discussion of TFA, analysis or product tends to be dominated by T, while process is oriented to O and P. The integration of these perspectives effectively bridges the gap between the technical analyst and the real world.

Deliberate incorporation of diverse perspectives in a TFA exercise will likely engender conflict. The differences must be managed so that richness is gained without undue disruption. One novel possibility to help reconcile differences that might enrich TFA is application of Bayesian techniques to blend human judgment with empirical data [72].

6. Using and assessing TFA

6.1. Utilization

Utility bluntly asks whether the intended users did indeed find the TFA information accessible and helpful. Moreover, did it influence decisions and actions?

The utilization track record of TFA is spotty. Experiences across many venues suggest that analytical information has much less influence on decision processes than analysts would hope for. A “complaint analysis” of TFA would, if performed, identify the major concerns as inaccuracy [73] and, we believe, incompleteness. Most technical users value analyses while others, including government personnel, incline toward comprehensiveness. This, of course, reflects the T focus of the technologists, as contrasted with the T-O-P concern of real-world decision makers. Research on utilization of empirical technology intelligence and assessment suggests process and content steps to foster utilization [74].

Techniques for improving the product and process of TFA include the following:

- Know the users; share expectations for the TFA.
- Involve the users in formulating the analysis and in the analytical processes as appropriate.
- Attend to organizational/institutional aspects—enlist support for the study; budget the TFA appropriately; strive to reduce perceived threats to various stakeholders posed by the TFA.
- Be clear on what content is needed—provide the "just right" blend of information to enable decision/action; deliver answers to the users' questions in preference to posing more questions.
- Build up credibility of the analysts (promulgate credentials); bolster credibility of the product (obtain endorsements); assure the methods used are familiar and acceptable to the users.
- Emphasize communication—recognize that each of the three perspective types calls for distinct modes of communication [31].
- Provide findings when needed (be timely).

6.2. Evaluation: the case of national foresight studies

Let us focus now on the evaluation of national Tech Foresight programs [75], both because this is inherently important and challenging and also because it enables us to explore certain considerations more deeply.

Unlike some more academic futures studies, for example, those aimed at general consciousness raising, Tech Foresight has a mission of informing specific decisions. However, that is only part of the picture. Governments may seek to use Tech Foresight as a tool to improve networks and build consensus in the S&T communities or in national, regional, or sectoral innovation systems. They may intend to use Tech Foresight as an awareness-raising tool, alerting industrialists to opportunities emerging in S&T or alerting researchers to the social or commercial significance and potential of their work.

As noted earlier, we must consider two aspects: product and process. Product-oriented work results, for example, in priority lists, reports arguing the case for a strategy in a particular field of S&T, proposals for reform of educational systems, etc. It is possible to count and document products (reports, webpages, etc.), to examine their diffusion (readership, citations, etc.), and even to get some estimate of their use. Process-oriented work results in network building, shared understanding, the formation of new alliances, bringing new participants into the innovation policy debate, etc. These consequences are harder to measure and monitor and will typically require more explicit examination—they will rarely be available as by-product data from the administration of a program.

Building on this, we can think about examining evaluation and use of Tech Foresight in terms of:

- Strategic intelligence about future issues [76] (questions of "accuracy," relevance, quality, etc.).
- Participation and networks: Involvement of stakeholders and experts from a wide range of sources (questions of recruitment, engagement, networking, etc.).
- Action: Feeding in to decision-making processes (questions of timeliness, appropriateness of presentation, policy impact, etc.).

Evaluation should establish, as far as possible, how far an activity has achieved—or how far it appears to be achieving—its intended outcomes.

There is no general-purpose toolkit for evaluating its influence and outcomes. Even establishing where a Tech Foresight process begins and ends is problematic.

In terms of the three orientations of Tech Foresight, we note the following:

- Futures: If accuracy is an issue, the assessment depends on the period that Tech Foresight addressed. In a short horizon (say, 5 years) critical technology exercise, this is not too serious a delay. But when Tech Foresight involves a time scale of 15 or more years, assessment is difficult—and its utility more problematic. A very stable Tech Foresight system is needed for such work—as in the case of Japan's STA/NISTEP forecasts.
- Participation and Networks: Examination of many aspects of the engagement of people in the Tech Foresight process and of the formation and consolidation of networks is best carried out in real time—memories get hazy rapidly and many of these activities go unrecorded. But many of the outputs and outcomes of such activities will take time to mature and require ex post investigation.
- Action: A major question here is that of attribution. We find that actions are often packaged as resulting from Tech Foresight, while in reality the decision makers use the reference to the study merely as a means of legitimation. Similarly, many actions may be taken that have their origins in the study but are not attributed to that source.

We distinguish several types of evaluation:

- Real-time evaluation takes place while the activity is underway.
- Most evaluations are "post hoc," conducted when the Tech Foresight process is completed or largely completed.
- Process evaluation examines how the Tech Foresight was conducted.
- Outcome evaluation examines outputs and achievements of the Tech Foresight.
- Assessing additionality: The key challenge here is determining the extent to which the activity would have taken place without the intervention of the Tech Foresight.
- Tech Foresight seeks to enlarge excessively short-term horizons and facilitate the formation of new networks around technologically and socially innovative activities. It

may be best evaluated ultimately in terms of its ability to change values and behavior in these directions [77]. This is the notion of behavioral additionality.

7. Challenges to TFA

The information technology era has provided powerful new capabilities that can be exploited to advance TFA, both product and process. We note three of them here:

1. Complex networks

(a) fluid networks that can reorganize as needed [78],
(b) swarming behavior, joining rapidly in temporary groupings for designated activities,
(c) virtual organizations,
(d) high-speed communications, permitting rapid adaptive management, and
(e) the Internet becoming a virtual parallel universe, with time the key dimension.

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2. Simulation modeling of complex adaptive systems

(a) cellular automata models of the diffusion of innovations and rebirth of extinct innovations [79,80],
(b) study of emergent aggregate system behavior based on locally available information, and
(c) models of heterogeneous agent population interactions in varying environments, for example, experimental economics [4,18].

3. Search of vast databases

(a) database tomography, for example, deriving profiles of R&D activity and generating innovation indicators [81],
(b) bibliometric analysis,
(c) environmental scanning to identify emerging needs, and
(d) morphological search for innovations, testing many permutations and combinations of systems variables.

The coming molecular technology era and the convergence of information and molecular technologies will similarly create new capabilities. Furthermore, we anticipate major structural changes in the economy, comparable to those experienced in the shift from agricultural to industrial to information economies. We expect that methods developed for S&T in nanotechnology, biotechnology, and materials science will also have a significant impact on TFA.

Let us now turn to some of the needs for TFA that we envision today:

1. Convergence is evident in the information and molecular technologies. It is perhaps most dramatically illustrated by the ‘‘human genome on a chip’’ now being marketed. Convergence is reflected in many other contexts: biology, physics, and chemistry are converging; actual and the virtual organizations are converging.

Question: How can the TFA process managers assure that scoping "experts" and other participants represent the convergent reality and not the "old" discipline orientations?

2. Drugs and medicines are more science intensive than any previous industrial sector. In 1997, the majority of patents in this industry already cited at least one peer-reviewed scientific article. Innovation processes differ from those in other industries. Now we are seeing

- combinatorial chemistry, allowing assessment of vast numbers of molecular variations through automated techniques to meet functional targets (e.g., drug design) and
- genetic recombination to improve proteins or create new ones.

Science-based forecasting is inherently more difficult than technology-based forecasting as much of it is basic and not directed to specific applications.

Question: What are techniques appropriate to TFA focused on science-intensive technologies?

3. Material development will be revolutionized by new capabilities such as

- molecular self-assembly to create desired material attributes, as well as computer processors and other functional devices, and
- combinations of semiconductor chip functionality, DNA reproducibility, and micro-fluidics and MEMs (micro-electromechanical devices) to achieve complex functionality in tiny, cheap, portable packages.

Question: Should the emphasis in TFA in this area shift from exploratory to normative methods appropriate to made-to-order materials?

4. There are many irreducible uncertainties inherent in the forces driving toward an unknown future beyond the short term and predictions need not be assumed to constitute necessary precursors to effective action. While foresight exercises can create several alternative scenarios to lead to examination of the uncertainties, they provide no means to develop robust strategies based on the large number of scenarios encompassing the spectrum of those uncertainties.

Question: Is the model proposed by RAND [44] suitable to overcome this foresight constraint?

5. Misperceptions associated with probability considerations are common because of the counterintuitive nature of that subject [31]. The certainty of surprises, such as catastrophic accidents and system breakdowns, underscores the importance of crisis management capability in both public and private sectors.

Questions: Will the TFA work tend to lull management into complacency? What steps can be taken to avoid it? How can the TFA process sweep in, and decision makers be persuaded to pay serious attention to, the likelihood of surprises, such as the occurrence of low probability–severe consequence events?

6. With the increasing pace of technological innovation characterizing the information and molecular eras, organizations must be evolutionary and adaptive. Management therefore

needs to self-organize from the bottom-up, be fluid, sense changes in the environment, and adapt quickly to them. It cannot be static in a highly dynamic environment. Example: In 1993, IBM management asked itself why it had so badly missed changes in the environment. Their strategic planners foresaw the impact of PCs and many other technological changes. But their operations did not change. Prices were simply raised to cover the growing erosion of their mainline markets. They feared turmoil and instability. But system instability is just as much a necessary phase as is stability in an evolving complex adaptive system (CAS). That is the essence of operating "at the edge of chaos" [82]. Opportunities as well as threats exist at that margin.

Questions: How can the TFA process mesh with this changed enterprise environment?

How can it accommodate rapid sensing of technological and environmental changes?

How can it facilitate distributed decision making emerging from bottom-up self-organization?

How can the combination of high-speed information sensing and processing, high connectivity, and highly flexible organization be integrated to facilitate rapid adaptability?

How does one apply the knowledge of CAS stability phase boundaries to galvanize technological change—presumably by expediting the onset of chaos (Schumpeter's "creative destruction")? How does one apply CAS phase knowledge to delay a phase change that management is unable or unready to handle—presumably by cutting feedback loops [10,11]?

7. Technological change, particularly in information and communication technologies, makes possible simultaneous centralization and decentralization, or globalization and localization, in public and private sectors.

Questions: How can TFA satisfy the diverse needs of these dichotomous management structures? Are special designs needed that cover this spectrum? What constitutes a good balance between the two extremes?

8. It has been suggested that technological evolution has striking similarities to biological evolution. The variants of an innovation—many tried with one successful and the others becoming extinct—suggest a process that mirrors biological evolution [83].

Questions: Is this model valid? Can artificial technological worlds be created by simulation modeling analogous to biological ones?

9. The Internet makes it possible to solicit judgments from many more stakeholders than before and facilitates dissemination of information, as the targeted audiences may be invited to provide feedback on intermediate and final results [84,85]. In practice, however, such distributed processes for mutual critiquing (e.g., electronic discussion forums) have not been particularly successful in large-scale Tech Foresight exercises [70,86].

Question: How can electronic discussions be effectively combined with personal interaction? Example: workshop participants asked to supply structured judgments and informal comments through a group support system that is used to aggregate these inputs for further discussion [87–89].

10. Simulation modeling has already been shown to be useful in studying the diffusion of innovations and the evolution of simple societies and trading patterns.

Questions: Can experimental economics models create a simulated market whereby viewpoints or tactics about the marketing of innovations may be tested? Beyond economics, can such models simulate social interactions well enough to inform decisions about the social consequences of technology? Can the TFA process, possibly in a simple prototype form, itself be subjected to a simulation modeling game to gain insight on the interplay and behavior of stakeholders and other parties?

11. Roadmapping is now being suggested as a tool for virtual innovation because the maps encourage visualization of new technological paths. Landscapes using metrics (represented by heights) can indicate the potential value of an innovative technology perceived by studying the roadmap. Even innovation games may be developed [90].

Question: Does this approach have merit? How can it be probed and evaluated?

A TFA workshop is planned in Seville in May 2004 to address questions such as these, bringing together European and American perspectives. It is hoped that this will stimulate research to advance TFA so that it will better inform science and technology policy and management.

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