WHAT DO WE KNOW ABOUT:

R&D METRICS IN TECHNOLOGY-DRIVEN ORGANIZATIONS

by

Eliezer Geisler
Professor and Associate Dean for Research
Stuart Graduate School of Business
Illinois Institute of Technology
Chicago, Illinois 60661
Tel: (312) 906-6532 Fax: (312) 906-6549
geisler@stuart.iit.edu

March 2002

Prepared by Invitation for the Center for Innovation Management Studies (CIMS) at North Carolina State University.

TABLE OF CONTENTS

INTRODUCTION

This report addresses the topic of R&D metrics in technology-driven organizations. More specifically, this report examines the state of knowledge on R&D metrics, which metrics are most useful, and what such R&D metrics tell us regarding the performance of technology-driven organizations.

The report starts with a discussion of why and what do we measure in the R&D/innovation continuum. Next it addresses the differences between input and output metrics, and provides a comprehensive listing of existing metrics. The relation between metrics and performance is also discussed in this report. Section four discusses the manner in which R&D metrics can measure the economic impacts of the R&D process, and the performance of R&D and technology-driven organizations. Finally, section five examines the state of knowledge about which metrics to use and in what specific conditions to use them, so that we may obtain a degree of utility from these metrics.

This report is a review of the state of knowledge in R&D metrics. It is not, however, a comprehensive nor exhaustive compendium of all R&D metrics and their possible uses. Selected metrics are emphasized in this report, as well as some uses that seem to be more common or that provide a better rate of utility. In all, this report provides a solid perspective of what we know about R&D metrics.

WHY AND WHAT DO WE MEASURE

The R&D/innovation process is a complex phenomenon. It starts with the generation of ideas, through research to development, prototyping, testing, engineering, design, and commercialization.[1] The process itself is an activity within the framework of the organization, consuming resources (inputs) and producing intellectual property in addition to actual products and other outputs. We are therefore concerned with the R&D/innovation phenomenon as composed of three levels or units of analysis: inputs to the process, the process or activity itself, and the outputs or outcomes from this activity.[2]

Why do we measure and apply R&D metrics to the R&D/innovation process? In general, we wish to evaluate an activity in order to assess the results it generated, the benefits that are accrued from it, and the degree of efficiency with which such outcomes had been created. In the R&D/innovation process we wish to evaluate the outcomes from the process, their relation to the inputs invested in the activity, and the ways and means by which we conducted the process itself.[3]

Evaluation of Inputs

The inputs to the R&D/innovation process in technology-driven organizations are considered investments to a critical activity and perhaps the most manipulated data utilized in assessment of R&D. These are tangible quantities that describe with relative precision the financial inputs to the process. They can also be allocated to the various components or sub-activities or projects within the process. Therefore, these inputs or investments in R&D can be used as a metric, allowing for evaluation and comparisons over time and among different technology-driven organizations.

Based on the assumption that there is a relationship between *levels* of investments in R&D and some measure of performance or outputs, the inputs to R&D can thus be used as a surrogate indicator of the process.[4] In this manner there is a widely-used metric constructed as an index. This is the metric of *R&D intensity*, which measures the level of investment in R&D (for a company, industry, or country)—per a selected economic quantity, such as sales or the Gross National Product.[5]

Industrial companies usually generate the metric of R&D intensity as the ratio of investments in R&D per figures of sales. This metric allows for comparisons over time and across companies and industries. It also leads to the establishment of benchmarks, averages, and their interpretation as characterization of "high" versus "low" technology industries and companies. American companies in the electronics sector (such as Hewlett-Packard) have consistently averaged a level of R&D intensity near the 20 percent mark. But, inputs to R&D can also be indexed as ratios of other variables. Figure 1 below shows such illustrative indices.

Figure 1
Illustrative Measures and Ratios of Expenditures or Inputs to R&D

Ratio of Expenditures or Inputs	Illustrative Studies

to R&D and –	
Expenditures/Sales	•Liao & Greenfield (1998)[21] •Franko (1989)[22]
Expenditures/Patents	•Henderson and Cockburn (1994)[23] •Penner-Hahn (1998)[24]
Expenditures: Internal R&D	•Nagarajan and Mitchell (1998)[25]
Effectiveness Index (% of revenue that is profit/% of revenue spent on R&D)	•Hauser (1998)[26]
Indexes: Cost Per Scientist & Engineer	•Geisler (1998)[27] •Lederman (1984)[28]
Expenditures for R&D/Assets	•Helfart (1997)[29]
Expenditures for R&D/Exports	•Ito and Pucik (1993)[30]

The reasons for employing input metrics of R&D are summarized in Figure 2. The use of gross expenditures in industrial R&D is found in the definition of high versus low technology when applied to companies and industries. This measure is similar to R&D intensity.

Figure 2
Summary of Key Reasons for Using Input Measures

- Expenditures/inputs to R&D and S&T (upstream and downstream) are easily quantifiable and amenable to statistical manipulations.
- Expenditures/inputs are easily and reliably defined in monetary terms, thus easily converted to ratios with other economic and financial measures.
- Expenditures/inputs can be used as proxies for more complex and less measurable phenomena, with such proxy relatively easily justifiable.
- As financial measures, expenditures/inputs can easily be computed over time to allow for inflationary effects to be reliably attenuated.
- Expenditures/inputs can be justified, with relative ease, as reliable measures in theoretical linkages of R&D or S&T effort with value created and outcomes generated from this effort.

The best uses of input metrics of R&D are in creating indices of intensity, and in "mixed"metrics, such as inputs (or expenditures) per certain measures of outcomes. As shown in Figure 1, they include inputs per sales, per patents, and per scientists and engineers. In some respects, such metrics provide a basis for assigning *costs* of various outcomes of R&D.[6]

Although inputs to R&D are an indication of the inventive activity in the technology-driven company, we do not possess to date a clear conclusion that the more a company spends on R&D, the more it will be technologically advanced or competitive. There are some benchmarks listed in the literature (such as R&D expenditures per sales), but these are established based on empirical data from successful companies, rather than solid theoretical frameworks. By and large, however, such metrics are powerful enough to indicate "best practices" of companies and industries, particularly because they compete with each other rather than with ideal systems of R&D and innovation.

Evaluation of Outputs

Outputs or outcomes from R&D are a more attractive basis for the construct of metrics. They represent performance of technology-driven organizations and are diverse enough to allow for a broad categorization of the results that R&D generates in the industrial company. Outputs from R&D may be defined as events, or material/physical objects such as products, processes, reports, or organizational/social/economic phenomena, such as savings and productivity.[7]

Outputs from R&D are seldom clearly and unequivocally defined in the literature. Various terms are used, primarily as surrogates or euphemisms. We find such terms as: "impacts," "effects," "spin-offs," "benefits," "returns," "value," and "payback." None of these is clearly defined and completely usable to measure the results from the R&D activity in the company. The reasons for this are the variety of outputs and the different measures used to assess them. Some outputs are intangible, defying measurement, others are masked behind more complex phenomena, such as the impacts of R&D on corporate growth. Another problem is the existence of a variety of recipients of outputs from R&D, thus making it difficult to establish who are the true "impactees" of the R&D activity.[8]

Categories of Outputs from R&D

There are five categories of outputs from R&D that have been identified and studied, and that are in current use to varying degrees: (1) bibliometrics; (2) patents; (3) peer-review; (4) economic and financial metrics; and (5) process-outcomes. In this report all five categories will be discussed. The format will be based on three main aspects of the metrics: (a) *Description* of the metric; (b) *Best Uses*; and (c) *Weaknesses* and problems with the metrics. Although the discussion of these metrics is clearly not exhaustive, it will reflect the extant literature and provide the reader with an adequate view of what we know about these output metrics.

In the discussion of the first four categories there is no distinction between outputs from the various components of R&D, namely, research, development, and technology. The outputs are assembled and examined for all the types of the inventive activity along the innovation continuum—from basic research to commercialization. However, a more specific differentiation is given in the process-outcomes model, where specific outputs are identified for the various *stages* of the innovation process.

R&D METRICS: MEASURING OUTPUTS

The Metric of Bibliometrics

Bibliometrics is a general term that includes the measures of R&D published outputs. In practice, there are the counts of publications in scientific and technical journals, and the indexing of citations of these publications by other writers in such outlets. The metric measures both the *quantity* and the *quality* of published outputs.

When the results and findings from the R&D activity are published, overtime a database of knowledge is thus created, and this becomes the state-of-the-art (SOA) of the discipline. So, within this database, scientists also compute the citation analysis, which is a process by which citations of articles in the literature are counted and analyzed to show and to study emerging patterns. *Bradford's Law* suggests that of over 8,000 scientific journals, about 2,000 publish 85% of all articles and 95% of cited articles. Some 200 journals (2.5%) publish 25% of relevant papers and 50% of all articles cited have been initially published in them. This means that there is a marked concentration of the important (most cited) papers published in a very small core of select (elite) journals.[9]

But this concentration is not an impediment to using citation indices to track developments in a discipline, or to compare the outputs (in bibliometric terms) between individuals and organizations. Thus, bibliometric measures are used to assess the *scientific* performance, in that the count of papers published and their subsequent citations indicate the level of scientific achievement.[10]

Counts of publications and citations may be also used to measure scientific productivity. In addition to a high concentration of select journals, there is also a phenomenon that most papers are published by a very small group of authors. Price's Law of Square Roots argues that about half of all the papers in a given discipline will be published by a number of authors equal to the square root of the total number of those who publish in the discipline. Clearly, this high concentration leads to the dominance of scientific (and technical) fields and disciplines by a very small number of scholars.[11]

Best Uses of Bibliometrics

Industrial companies use bibliometric measures in two complementary forms. The first is the evolution of the performance of their scientific personnel within the R&D unit and activity. The second is the evaluation of the R&D functions within the firm.

In general, companies use bibliometrics as an integral part of their system that evaluates scientific and technical employees. Widely-published corporate researchers indicate an outstanding R&D group and generate much-desired reputation and prestige for the company.[12]

Companies hold the belief that the reputation of their scientific cadre will permeate onto their customers, other stakeholders, and the general public.[13] In the pharmaceutical industry such beliefs are supported by empirical data. Recent studies have found a correlation between the interaction of these firms with the scientific community—and their success in drug discovery. Another finding indicates a positive correlation between the number of scientific "stars" employed by a company and the use of such "stardom" criteria for promotion of its R&D personnel.[14]

Figure 3
Strength of Bibliometrics in the Evaluation of S&T

A. STRUCTURE
- Bibliometrics can be applied to various levels of generators of intellectual outputs, such as individuals, groups, institutions, and countries.
- The cost of collecting the data and conducting meaningful analysis is relatively adequate.
- The measures are already built into the metric, thus there is no need to establish them and to test them for validity.

B. MEASUREMENT
- Bibliometrics allows for quantitative assessment of S&T outputs by counts of papers and citations, and for qualitative assessment by analysis of core journals and their relative impacts.
- Bibliometrics and its analysis is a relatively straightforward approach, relying on a few assumptions.

C. REPRESENTATION
- Bibliometrics can be applied to the entire spectrum of S&T where outcomes take the form of reports, papers, and citations.
- Bibliometrics, through citation analysis, helps to determine the role that individuals and institutions have in the evolution of a scientific discipline.
- Bibliometrics analysis allows for the identification of trends and developments in science and technology and in scientific disciplines.
- By convention, bibliometrics has been accepted by the S&T community as valid representation of the outputs from intellectual and inventive activities.

This list is not exhaustive nor in any specific order.

In summary, industrial companies utilize bibliometrics because they believe that by supporting a climate of research and publishing, the firm fosters the intellectual enrichment of its personnel. This, in turn, will ultimately translate into contributions to the bottom-line through innovations, added prestige, and sustained competitiveness.

Problems and Shortcomings of the Use of Bibliometrics

Bibliometrics are best employed in the evaluation of the scientific component of knowledge creation. But, when applied downstream the innovation process, this metric describes only one, perhaps very small, attribute of the phenomenon of R&D and technological development, utilization, and commercialization by the firm.

Bibliometrics measure the transfer of scientific knowledge, and as such encourages the diffusion of scientific outcomes. Such focus on communication helped to make science and research more accessible.

Figure 4
Weaknesses and Problems with Bibliometrics

A. COVERAGE

- Published articles are only one measure of outputs from scientific activity, hence the metric does not cover reports, other written communications such as electronic mail, letters, and personal communiques.
- Articles published in peer-reviewed journals and their citations analysis disregard the outputs and intellectual contributions in articles published in technical outlets, as well as work-in-progress.

B. MEASUREMENT

- The "Pied-Piper Effect": bibliometrics, particularly citation analysis, measures influence, not quality. Citations are selective and refer to those papers that "toe the line" and do not "rock the boat."
- Published articles measure output in a given subdiscipline or discipline, hence cross-disciplinary analysis may be difficult to validate, because of the different structure and procedures of the scientific investigation in each discipline; particularly ease and rate of publishing, and the nature of the peer selection processes (the "Apples and Oranges Effect").
- Counts of publications and citations analysis tend to disregard the influence of the stage in the life of the discipline or area, such as "mature" area versus an "evolving" new area (the "Gulliver Effect").

C. GENERALIZABILITY

- Counts of publications and citations lack a standard for their validation as a measure of quality. When compared with inputs (investments in R&D), the resulting analysis relies on covariation of two distinct phenomena and disregards the complexities of the R&D process.
- The only standard for validation of bibliometrics is convention of a small and elite group of influential scientists.
- As in the "Hindsight" project, the problem is: "How far in time should citations go?" Should articles in quantum mechanics cite Einstein's work *and* that of the Greek philosophers and mathematicians? Citations are thus highly selective and refer to a relatively short timeframe, preferably within a few years of the focal paper in which they are cited.

D. BIASES

- Because of the almost incestuous nature of the small group of prolific publishers, there is an inordinate amount of self-citations and citations of "friends" and other members of this elite group. Thus, authors who publish in areas that are near the boundaries of their discipline or in cross-disciplinary topics are much less likely to be published in top journals or to be cited in them.
- Criteria for the selection of articles for publication in juried journals are built into the process and will bias the resultant counts of papers and citations in favor of those authors preferred by the reviewers.
- Selection and analyses of key journals and the interpretation of the counts of papers and citations are based on assumptions of validity of these metrics as measures of quality and internal dynamics of the discipline. Such assumptions are the product of opinions and judgment, hence biased.
- The selection and analysis process of key journals and papers to be included in this process is biased in that analysts who are generally outside the discipline or the area impose their own views and criteria in making determinations and drawing conclusions that transcend the data.*This list is not exhaustive nor in any specific order.*

Yet, bibliometrics are also limited by the influence of other dimensions downstream the innovation process. For example, companies may have stellar performance in publications and citations, yet lack the ability to apply sufficient commercialization effort, so that its competitiveness is protected and enhanced. This is the case of the gap between R&D and the commercial or business side of the firm, which has been amply studied. A strong scientific base in the firm is not a guarantee for a strong showing in the marketplace. Hence, bibliometrics must be regarded as a limited measure of the upstream activity and outputs, whereas other metrics should be used to assess downstream activities of the innovation process.[15]

Co-word Analysis and Data Mining

The bibliometric set of measures of the outputs from R&D provide a count of the number of items. Co-word analysis is concerned with the actual content of these output counts. This term is also expressed in the following techniques: KDD (Knowledge Discovery in Databases), DT (Database Tomography), and TDM (Textual Data Mining), all of which are means to conduct content analysis.

The underlying assumption for co-word analysis is that scientific ideas, concepts, and findings are reported in written form by using simple text and selected technical terms which are also a combination of words. Since these words describe scientific findings, they will be repeated (co-occur) in other texts that report similar findings.

The model used here is one of *frequencies* of occurrence of joint keywords that portray the evaluation of ideas and concepts—as they appear in the scientific literature.[16]

Benefits from Co-word Analysis

Co-word Analysis offers a technique that allows for dynamic comparisons across disciplines. By tracing the measurement of keywords, analysts are able to show the interdisciplinary nature of scientific evolution. When combined with comparative counts of citations across disciplines, a structure of networking seems to emerge.[17]

This benefit makes Co-word Analysis a tool that identifies patterns of the evolution and movement of scientific thought. As such it is being increasingly used to evaluate the productivity of individual researchers and to assess the impacts of scientific journals. For example, when a new concept is assigned by researchers, this concept is diffused throughout the literature and the rate of diffusion can be assessed by Co-word Analysis.

These concepts are not only specific terms, such as "core competencies" or "cloning," but also nomenclature that applied to fields, sub-fields, and topics in scientific investigation. For example, nanotechnology is such a conceptual framework for research that encompasses a variety of sub-areas, each endowed with a title. Co-word analysis can trace the structural development of research in nanotechnology across various disciplines.

Weaknesses and Problems of Co-Word Analysis

There are four key problems with Co-word Analysis. The first is the over-reliance on the validity of the search criteria that are used in selecting the keywords to be counted. The terms are selected by interested parties, such as authors, editors, and reviewers, and therefore are somewhat biased.

Secondly, the technique of Co-word Analysis is utilized to achieve objectives beyond its original intent—to retrieve information from databases and to establish potential patterns and structures. Rather, this technique is used as an evaluation tool to assess the performance of research groups and the impact of individual journals. Such evaluations may be tainted because the tool used in them is not geared for the job.

The third problem is the repetition of keywords simply because they were artificially included by reviewers and evaluators. This adds to the bias of the metric. Finally, this technique does not make use of free text, or the full text of scientific documents. Keywords may indicate only a portion of the full content of scientific documents, and may fail to measure the rich blend of scientific thought and rationale as embedded in the text itself.[18]

Benefits and Weaknesses of Textual Data Mining (TDM)

By its nature, Data Mining is a technique that extracts information from both structured and unstructured databases by considering the entire stock of words, quantities, and images. TDM seems to be a beneficial metric since it focuses on unstructured or free-text, as it searches for words, sentences, and constructs that appear in the literature. TDM thus goes beyond keywords, identifying instead scientific *themes*, the relationship among these themes, and their evolution in the database.[19]

Some of the weaknesses of this metric are summarized in Figure 5 below. The main problems seem to be interpretation, reasoning, and the quality of the data being mined.

Figure 5
Some Weaknesses and Problems with Data Mining (DM)

- With all its ability to generate models, *interpretation* of the implications of patterns uncovered *is still the key element*.
- In essence, DM *mainly saves time and effort* of manually going through large databases.
- Effectiveness of DM *depends on the quality of the data* and data sources.
- DM is *difficult to implement*, *costly*, and requires experienced workers.
- *Patterns* and relationships identified by DM may be *largely of little value*.
- Mix of techniques used may not be complementary but yield *conflicting scenarios*.
- "Hype" with DM may have led to *overpromising*.
- Overreliance on computerized discovery of patterns may *diminish* the *role of human reasoning*.

This list is illustrative and not in any particular order or ranking.

The analyst is thus free to interpret the data, even after such data has been the object of computer analyses. The creation of meaningful patterns and worthwhile scenarios remains largely the best attempts by analysts to interpret complex data. This leads to problems of imputation, as well as biases of pre-established notions and beliefs.(20)

Mapping of R&D and Technology Roadmaps

Mapping of R&D is a technique that provides interpretation of co-word analysis and the frequencies of keywords in the literature. Proponents and advocates of maps of science and technology argue that such maps offer visualizations of structures and structural changes in science.

In the case of technology, maps or roadmaps are tools that portray the relation between technology and its subsequent outcomes. This is the portrayal of prospective movement along the innovation process, as technological outcomes are transformed into commercial products.[21]

Strengths and Benefits of Technology Roadmaps

Technology roadmaps are both a document and a process. They describe stages of development and the evolution of technology, and the barriers that commercialization of such technology will encounter. As such, these roadmaps are a powerful decision aid for managers of technology and managers of business processes. By describing critical aspects of the innovation and commercialization processes, roadmaps allow for the meeting of the minds of the generators and users of technology. The generators can apply the roadmap to ask: "Which technologies (and the R&D that generates them) are more likely to lead to commercial uses?" whereas users may ask: "Which technologies are needed to make these products feasible and commercially successful?" Roadmaps can be applied to existing products in need of innovation (retrospectively) or to potential products.

Another benefit of technology roadmaps is their ability to provide a framework for analysis and evaluation of the innovation process—to which both technologists and business managers can subscribe. This framework also allows for anchoring of the strategic integration of technology, R&D, and business objectives in the industrial company.[22]

Weaknesses and Problems of Technology Roadmaps

As they are intended to be planning and strategy tools, technology roadmaps have problems that are usually found in such techniques, including lack of quality standards, partial representation of the phenomenon, and the lack of an underlying theory that explains the structures depicted in the maps. Figure 6 lists the four categories of problems: technical, managerial, organizational, and metrics-related.

Figure 6
Some Weaknesses and Problems with Technology Roadmaps

A. TECHNICAL PROBLEMS

- Lack of independent tests of quality and reference standards for benchmarking.
- Design of roadmap may be too conservative or too optimistic, reflecting difficulties in forecasting of the technology and its potential applications.
- Chronic underestimation of time and effort required for design and implementation of roadmap.

B. MANAGERIAL PROBLEMS

- Management commitment not always secured because roadmaps are considered a mere decision aid.
- Objectives for roadmaps are established by managers without awareness of what technology can and should do.

C. ORGANIZATIONAL PROBLEMS

- Technology roadmaps are integrative tools, so when an organization is functionally structured, there are difficulties in having a cross-functional activity charted.
- Reengineering and restructuring activities tend to disrupt the implementation of roadmaps.

D. METRICS

- Difficulties in evaluating quality.
- Complexity of roadmaps makes it difficult to use accurate metrics.

The first three categories are common to planning techniques, but the fourth (metrics) is somewhat unique to technology roadmaps. This category includes two problems: evaluation of quality and complexity. Due to the fact that technology roadmaps extend their conceptual reach to the innovation process, they deal with a variety of stages and sub-phenomena. Thus, they portray a very complex set of scenarios that make it very difficult to use precise and accurate metrics. It is also difficult to assess the quality of the stages in the process, and to establish benchmarks.[23]

Best Uses of Technology Roadmaps

Two cases of successful use of technology roadmaps come to mind and are described below. The first is the technology roadmap process practiced at Motorola. The second is the product-technology roadmap process practiced by Phillips Electronics.

The Motorola Roadmap. Motorola is a communication and electronics industrial giant. In the mid-1980s it developed and used corporate plans that focused on technological development. These plans are documented in technology roadmaps. Two kinds of roadmaps were used: (1) *Emerging Technology Roadmap,* which tracks the development and potential of the individual technology, and (2) *Product Technology Roadmap,* which tracks the technological basis of the company's product lines.

One important component of the Product Technology Roadmap is a matrix that generates the technological requirements for future products. It is obtained by the summaries of product plans and technological forecasts. This integrative viewpoint of where the company is headed and the role of technology in its future is a fundamental benefit of the roadmap.

The Phillips Roadmap. Phillips Electronics is also a worldwide company based in the Netherlands. As in the case of Motorola, the Phillips technology roadmaps are designed to provide a better link between products and the technologies that are embedded in them.

In particular, the Phillips Technology roadmaps use a model of the Innovation Matrix in which questions related to technology are being asked, such as, Is it feasible? Do we want it? How do we do it? and How is the specific technology integrated into the product?

Roadmaps allow the company to identify gaps in technology (present and future) and to provide managers with a solid perspective over time of the degree to which their technology in integrated in the company's product lines.

The Metric of Peer Review

What is peer review and what do we know about its benefits, problems, and best uses? The first set of output metrics was quantitative: the counts of bibliometrics and the mapping of the evolution of such outputs downstream the innovation process. Peer review is a judgment or qualitative metric. It is based on a process by which a selective jury of experts in a given field is asked to evaluate the scientific activity, its outcomes, and its performers. Usually the criteria recommended for peer review are very broad, thus leaving much latitude to the experts to exercise their opinions and personal perspectives.[24]

The criteria for peer review evaluation used by industry are listed in Figure 7 below.

Figure 7
Peer-Review Criteria Used by Industry

ILLUSTRATIVE REVIEW CRITERIA

- Potential returns and payoff within a foreseeable time line.
- Probability of technical success within a project time-cost estimate.
- Probability of commercial success within a given time frame.
- Relevancy to corporate strategic plan.
- Relevancy to product lines and businesses.
- Amount and sufficiency of resources available.
- Prior experience with the project team and with similar research.
- Level of senior management's support for such research.
- Relation to the overall corporate R&D portfolio.
- Relation to an established need from marketing or another unit in the corporation, such as clients, users, regulators, or vendors.

These are examples of criteria used by peer-review committees.

In the industrial company, peer review is a process that employs a mix of evaluation teams composed of members from the scientific and technical units, and from the executive or business side of the firm. These committees evaluate two dimensions of R&D projects: (1) probability of *scientific/technical success*, and (2) probability or potential for *commercial success*.

Corporate committees or ad-hoc groups of evaluators in the firm utilize three categories for peer review of R&D projects. The first such category is the potential success of the proposed work. Success is defined as both technical *and* commercial. Probabilities are subjectively computed by members of the committee (peers) and a rating system is usually established to rank projects. (25)

The second category contains criteria of economic payoffs and financial returns from R&D.[26] Expenditures for corporate R&D and the outputs from R&D are usually evaluated against traditional financial indices, primarily those of return on investment, “dollarization,” payback on investments, and sales. These criteria are considered by the peer review committees when they rate the projects, in both prospective and retrospective manners.

The third category includes criteria related to the relevancy of the proposed R&D to the company’s product lines and businesses. The peers judge the projects in accordance with their knowledge of the strategic direction of the company, its product lines, and the distribution of these product-lines in future marketing efforts.

Once the criteria are utilized in ranking projects, the committee establishes a *cutoff point* below which R&D projects will not be funded. Similar procedures are also used when external reviewers (or peers) are used to judge the company’s R&D.

Strengths and Benefits from Peer Review

The benefits from peer review are illustrated in Figure 8. These may be grouped into two categories. The first generales a measure of quality control and scientific accountability. This measure is essentially the thin line of control for scientific integrity. Because of the way we define the scientific method, and the high degree of specialization and expertise required in R&D—peer review remains the operational control process, designed to distinguish between "poor" and "good" R&D.

Figure 8
Illustrative Strengths and Benefits from Peer Review

ILLUSTRATIVE STRENGTHS/BENEFITS
• Provides judgmental assessment by qualified experts in the S&T discipline and subspecialty. • Provides a measure of quality control by preventing acceptance of "bad" science. • Provides detailed opinions, comments, and suggestions from acceptable and respected peers. • Allows for checks and balances among diverse opinions and "schools of thought." • The peer-review process is understood by all participants. • Provides scientific accountability. • Relies on the intellectual resources of the S&T community. • The process is rational, valid, and fair. • Although qualitative, peer-review assessments provide adequate data for decisions on allocation of resources for S&T.

Not necessarily in any order of importance or priority.

Weaknesses and Problems of Peer Review

Illustrative problems of peer review are listed in Figure 9. There are two groups of weaknesses. The first are problems due to the biases that are inherent in human behavior, so that peers who review the work of other R&D personnel insert such biases into their judgment. A second group of shortcomings of peer review is the process variables, in which judgmental evaluation is given great importance in determining the success and survival of R&D projects. Risk is minimized and "rocking the boat" is discouraged.

Figure 9
Illustrative Weaknesses and Problems with Peer Review

ILLUSTRATIVE WEAKNESSES/PROBLEMS
• Delphi-type surveys are constrained by time, limited response rate, and preponderance of conservative views.
• Reviewers may show bias, jealousy, revenge, and intolerance toward other authors.
• Reviewers may protect their own "turf" and subspecialty by promoting papers in these areas.
• Reviews are cursory, hence there is no guarantee that "good" science will prevail and "bad" be rejected.
• Reviewers and editors tend to stick to existing paradigms in their disciplines and reject change.
• Editors wield inordinate power and channel the discipline in their preferred direction, rather than in a "bottom up" approach from the bench scientists.
• Secrecy of the process.
• Tendency to prefer established, well-published scientists.
• Problems with rating and raters, based on judgmental data.
• Cultural bias toward English-speaking publications.
• Good, specialized reviewers are increasingly hard to recruit.

Not necessarily in any order of importance or priority.

However, although peer review suffers from biases, it remains an indispensible metric, used primarily to determine the quality of R&D.

The Metric of Patents

What Are Patents and How Do They Measure S&T Outputs?

The count of patents as a metric of technology progress has long been favored by economists and by industrial companies. There are several reasons for their choice. First, patents can be counted, thus can be quantitatively applied in economic models. Second, patents represent a clearly defined output in the invention and innovation process, hence allow for a realistic model of technology progress and its link (via patents) to economic progress. Third, patents represent a legal document describing intellectual property rights, hence serving as a strong indicator of individual and corporate assets. Finally, patents serve as an indicator of both ends of the innovation process: as measures of outcomes from R&D activity, and as economic instruments by which companies compete in the marketplace.

Patents are basically an inventor's registration with the appropriate government agency of the technical description and potential applications of the inventor's novelty, not previously so registered. Inventors may be individual or corporations, and such registration protects them for a determined period of time so they can exploit the economic benefits that may accrue from the invention.[27]

As a measure of S&T, patents are considered by many economists to be indicators not only of inventive activity but also of technological progress and change at the industrial and national levels. Patents are considered to be "tangible evidence of technological innovation,"therefore they are considered a reliable measure of technological capability and achievement.

Economists are also interested in how well patents measure the value of innovations and intellectual property. To be of value to the patenting organization, patents must be able to provide protection of intellectual property, thus to enhance the organization's competitive strength that technology offers its owners.

Traditionally, patents were studied in connection with the link between incentives for R&D and monopolistic advantages from patenting activities. More recently patents have also been explored as an instrument that promotes sequential innovations, so that a stream of inventive activities can stimulate economic progress.

Patents as Measures of R&D Inputs

What are the attributes of patents that make them acceptable surrogate measures of R&D inputs? First, economists have found a correlation between R&D expenditures and levels of patenting. Such covariation suggested that patent activity may serve to indicate the level of R&D, in particular since the time lag between R&D and patenting was not a variable in the relationship.

Second, patents are a measure applied across industries and companies within them, so that a comparison can be drawn among different disciplines and organizations. The format of this measure is uniform on an international basis, hence comparisons can be made across countries.

Finally, patents contain information on the invention to an extent that allows for a possible gross reconstruction of the R&D effort that was expended into the invention. So, regardless of the different patenting strategies among companies and industries, the more companies invest in R&D, the higher their overall patent activity.

Patents as Measures of R&D Outputs

A different perspective and other characteristics are attributed to count of patents as a measure of R&D outputs and as an indicator of the outcomes from the innovation process. In general, patents are viewed as indicators of the potential market applications of the invention. Hence there may be economic impacts from patented inventions that appear in the form of new products, technological improvements, and shifts in markets.

Perhaps one of the more important factors inherent in a patent that makes it an acceptable measure of R&D outputs is the content of its documentation. In addition to the *count* of patents, the patent application submitted to the granting authorities contains a particularly revealing source of information.[28]

Patent databases have been in existence since the late Middle Ages. Patent applications contain information on the invention itself, and on some "prior art" in the area of the invention. Taken as a set of converging items, patent applications from a company offer an incisive look at the areas in which the company has been working, and its successes and accomplishments, reflected in its desire to gain protection from competitors via patents.

Furthermore, trained analysts are able to extract from a patent data set some indications of a company's level of R&D effort required to arrive at this level of patenting. Analysis of patent data may also indicate subsequent economic activity (e.g., sales and profits), which may then be attributed to patenting and to the R&D effort that had generated them.

By using a method equivalent to "knowledge production function," Crepon and Duguet (1997) have advanced the notion of the *Patent Equation*.[29] They studied the relationship between R&D investments and patent applications by a sample of 698 French manufacturing companies in the period 1984-1989. Patents were considered a measure of incremental knowledge for the firm, hence improving the stock of knowledge which leads to improved innovation. They concluded that "past successes in the production of innovation (patents) increases the efficiency of the R&D-innovation relationship" (p. 262). But they also concluded that: "the past number of patents has a nonlinear effect: small but positive numbers of past innovations affect positively the production of innovation but the effect slowly vanishes as the number of innovation increases" (p. 262).

Patents, Quality, and Their Impacts

How do patents affect the economic outcomes of the firm? As seen in the previous section, patents are viewed as measures of investments in the knowledge stock, so they contribute to improved innovation. But the link between patents and such variables as sales and market share is credited to several other factors.

One such factor is *quality*, which is usually indicated by (1) counts of patents granted, (2) patent applications in major foreign markets, and (3) patent citations as background for other patents. Since several studies have found a positive relationship between patenting and corporate performance, it would be logical to assume that the higher the quality of these patents, the higher the technological base of the firm and the more advanced its pool of skills—hence a better starting position to create innovations and to impact the marketplace.

Strengths And Benefits From Patents

The count, citation analysis, and examination of the content of patent applications (and valid patents) all may lead toward several benefits, some of which are shown in Figure 10. The figure summarizes the strengths of patents (as a metric of R&D) and their benefits.

Figure 10
Strengths and Benefits of Patents

A. METHODOLOGY
- Patent data are quantitative measures.
- Patent databases have been in existence for many years.
- Patent data are relatively easy to manipulate.
- Patent data can be related to other economic/financial measures.
- Patent citations allow for co-citation analyses.

B. STRUCTURE
- Patent data have a similar structure as a legal document.
- Contain revealing information.
- Indicate levels of S&T effort.
- Similar items of information facilitates cross-industries and even cross-national comparison.

C. IMPACTS AND CONTRIBUTIONS
- Considered as a link between S&T and firm performance, patents offer an elegant way of establishing such a link.
- Patents are viewed as indication of technological achievements.
- Patents are viewed as measures of the knowledge-base.
- Patents are viewed as measures of the quality of S&T.

From a methodology perspective, patents are an attractive database, easily manipulable, and allowing for time-series and cross-industries comparative analyses. Structurally, patent data include relevant information whose content offers a wealth of knowledge about the patent.

But above all, patents are viewed as a link between R&D and the economic performance of the firm. As such they are elevated to the level of concrete measures of the innovation phenomenon.

Yet economists have long emphasized the role that patents play in establishing a strong competitive position for a firm in its industry. Cardon and Sasaki (1991),[30] for example, have argued that "a patent grants the winner monopoly power" (p. 324) and "if firms search on the same R&D path, as soon as the first firm completes development and patents the new technology, other firms must switch to another technology and start development afresh" (p. 325). This phenomenon, the authors claim, helps to prolong the patenting firm's monopoly, so patent protection "becomes a contributor to preemptive strategy."

So patents effectively provide the firm with a legal instrument that compels the competition to accept temporary monopolistic domain of the patenting company in a given technology. The patenting firm that integrates such possibilities into its strategic planning may find itself in a comparatively advantageous position.

Weaknesses And Problems

There are three major weaknesses in the use of patents as a metric of R&D: (1) organizations have different propensities in their patenting decisions, (2) there are distortions in the marketplace, and (3) the link between S&T and corporate performance (that patents presumably measure) is not supported by theory. These and other weaknesses are listed in Figure 11.

Figure 11
Weaknesses and Problems of Patents

A. FIRM-INDUSTRY STRATEGY
- There are marked differences among firms and industries in the propensity to patent inventions.
- Industrial firms only spend less than 1/3 of their R&D effort to develop new products that would result in patents.[30]
- Firm-specific information in patent data impacts decisions to invest in S&T.
- Past performance of patenting activity impacts the propensity to patent.

B. MARKET CONSIDERATIONS
- Distortions in market due to monopolistic behavior.
- Market factors may impact patenting behavior.
- Patents do not always lead to commercial applications.

C. STRUCTURE AND METHODOLOGY
- Patents represent only a small portion of the actual R&D and S&T effort.
- Patents reveal only selected information about S&T.
- Patentable inventions have become increasingly harder to discover.
- The link S&T-Patents-Performance is based on covariation methodology and lacks a description of the process and factors that impact this presumed link.
- There is a lack of a theory to explain how patents contribute to performance and to strategic advantages (except for the link to possibly monopolistic manifestations of the power from patent protection).

Although these shortcomings are, in the aggregate, powerful enough to cast doubt on the validity of patent counts and analysis as a viable metric, universities, industrial companies, and government laboratories nevertheless use this metric for a variety of evaluations.

Best Uses of Patents

The most prevalent use of patents by industrial firms is in affording protection to intellectual property. Following a decision by the U.S. Supreme Court in 1996 that gave judges added latitude in deciding patent cases, there has developed a climate whereby companies are more inclined to litigate issues of intellectual property.

An illustrative case is the invention of the magnetic resonance imaging (MRI). Fonar Corporation, whose Dr. Damradian had a patent of the scanning technology that forms the basis of the MRI, sued for patent infringement. The company filed suits against General Electric, Siemens, Phillips, Johnson &

Johnson, and Hitachi. All of Fonar's opponents, except General Electric, settled out of court. In June 1997 a U.S. Federal Court ruled in favor of Fonar.[31]

A different use of patents allows companies to chart their strategic growth in directions otherwise deemed unreasonable and risky. Consider the case of Monsanto and its herbicide, Glyphosate, sold under the brand name of "Roundup." As the most successful herbicide, Roundup's original patent was to expire in the year 2000. However, due to the protection the patent afforded Monsanto, the company has developed new crops (such as soy beans) that are genetically engineered to tolerate Roundup. The company has obtained a patent on these crops, so it continues to maintain its market superiority. Instead of the exclusive hold on the herbicide, it now has the exclusive rights to the plants themselves.

A third use of patents and their data is for mapping out competitors' strategy. Patent data are analyzed to obtain a picture of a competing company's technological competencies. In this fashion patent data are used for protection of intellectual property, but they also help to disclose the strengths and weaknesses of the patenting company.

Are patents a credible metric of the R&D effort and outcomes? Although of extensive use because of their legal and economic characteristics, patent counts and analyses provide only a limited measure of the R&D activity. Patents contain valuable information about the inventions and the effort that has led to them, but they are not sufficient to be used as a sole metric of R&D.

When used in combination with other metrics, patents offer a manageable piece of data on the level of R&D effort by individuals and firms. But one should not confuse the relative ease in obtaining such data and their manipulation with the amount of knowledge that such data provide on the R&D phenomenon. Such knowledge is limited, bounded by the weaknesses and problems displayed in Figure 11. In particular, patents—as a metric—are of limited value as a metric of R&D because of different patenting behaviors by companies, and the fact that they are designed to be a legal instrument offering some measure of protection of intellectual property. They were not specifically designed as a metric of the R&D activity nor its outcomes.

Economic and Financial Metrics

At both firm and industry levels economists have been trying to assess the impacts of R&D on the firm and the industry by utilizing financial measures such as return on investment and cost-effectiveness. Although this effort has not yielded encouraging results, the attractiveness of being able to compute expected financial return (return on investment—ROI, or return on assets—ROA) has fueled many such attempts.

As early as 1971, Richard Foster had applied the method of internal rate of return from the R&D budgets of four industries and the IBM corporation. He used a straightforward approach which related the cash flow to expenditures for R&D. However, the assumptions underlying his key equations were unrealistic. In particular he assumed that it would be feasible to allocate with precision R&D investments to new products, and that it is feasible to identify and to precisely compute the proportions of sales and profits that resulted from R&D.[32]

More recently several authors have argued that such a direct approach is tenuous, insufficient, and even misleading. Some listed the imprecision of measurement and problems with allocation of overhead to R&D as key factors undermining the use of ROI. They also argued that ROI would be appropriate to estimate the returns from development projects that are "particularly well defined, short term." Finally, they also proposed the mix of financial measures with other subjective judgments of the R&D effort.

In the case of information technology, many industry managers have argued that not all of the investments in IT can be applied to a rigorous ROI technique. Some returns can be satisfactorily isolated and defined, hence can also be estimated by ROI methodology. Similar concerns and limitations are also frequently cited for the applicability of the ROA method.

Some economists have considered various factors and circumstances that affect investments in R&D and S&T. One such argument was that network externalities may contribute to a company's decision to partake in an R&D race, thus boosting its level of investments in the generation of new products and services. Thus, regulations regarding price and entry, as well as standards imposed early on by the industry, may affect the R&D race in the opposite direction, by removing incentives for conducting massive R&D.

We also find in the literature studies of the *social* rates of return to R&D by means of total factor productivity growth. These had underestimated investments in R&D. Since the said literature estimated about 30% social return from R&D, and with a private ROI of 7-14%, an economy such as the United States should increase its investments in R&D two- to fourfold.

So, although used to some extent by industrial companies to measure the returns from their R&D, the methods of ROI and ROA are largely limited. Constraints of measurement issues, the nature of the R&D process, and externalities—all impinge on the organization's ability to accurately assess the financial returns from R&D investments.

R&D Spillovers

Among the financial and economic measures of R&D evaluation, the focus on R&D spillovers has contributed to a more precise albeit elaborate exploration of how R&D impacts the economy. R&D spillovers are roughly defined by economists as the impacts that outcomes from R&D by other firms have on the effectiveness and outputs of any given firm's own R&D effort.

A summary of what we know shows that the key question for economists is: Why are there differences among firms in the resources they choose to invest in R&D? Spillovers may help explain the existence of technological opportunities in the industry, but they do not satisfactorily explain such differences. The question is: Does it work because a firm benefits from the efforts of others or is it just a reflection of spatially correlated technological opportunities?

Some studies explored the impacts of R&D spillovers on the firm's R&D productivity. They concluded that "firms whose research is in areas where there is much research by other firms have, on average, more patents per dollar of R&D, and a higher return to R&D in terms of accounting profits or market value."[33] It was also found that firms that had a very low R&D effort tend to be negatively influenced by their peers in industries that have a high R&D effort. We recognized the limitations of the evidence as "circumstantial," and the various assumptions that have to be made, and other measurement problems.

R&D spillovers are therefore considered to be externalities that provide inputs to the R&D activity on the firm. This aspect of R&D spillovers may be useful in attempting to explain variations in the firms' investments in R&D. But, if spillovers could also be considered in terms of the *process* by which they "transfer" value to other firms, then the door may be opened for assessment beyond the anecdoted constraints.

R&D Productivity and R&D Impacts

The literature on R&D spillovers and models of growth contains research dealing with two distinct phenomena, albeit related: (1) effects of R&D spillovers on the firm's *own* R&D and its productivity measured by outputs such as patents, and (2) effects of R&D spillovers on the organization and beyond. Although the patenting activity by firms represents a market distortion that influences the decision of a firm to invest in R&D, nevertheless patents are first a measure of the productivity of the inventive activity (R&D) in the firm.

The difficulties in isolating and measuring the precise impacts on R&D productivity and R&D impacts on the organization and beyond are an additional constraint in assessing the link between R&D, productivity, and performance. Some studies may have achieved relative success by exploring aggregate figures, but at the level of the individual firm this link remains mainly anecdotal.

Strengths and Benefits of Financial Metrics

Economic and financial metrics for evaluating R&D are a very attractive means to measure outputs from the R&D activity. They offer not only quantitative measures, but also allow for links to traditional financial indicators in the firm. Figure 12 lists some of these strengths and benefits.

Figure 12
Strengths of the Economic/Financial Metrics

- Offers quantitative measures that describe economic factors, variables, and phenomena.
- Allows for the gathering of time-series data of expenditures and other economic/financial variables, hence makes possible the statistical correlations among these data sets.
- Allows for comparisons with financial measures of other (non-R&D) activities in the firm and in the industry.
- Under certain assumptions, conclusions can be drawn on the economic viability of R&D and the allocation of economic resources to this effort.
- Allows for a link (causal or relational) between investments in R&D or S&T, their economic outputs, and accounting and managerial ratios and indices of financial activity and financial success.
- Allows for the quantification of certain externalities and their relation to the R&D function.
- Inserts an econometric input to the inventive effort.

This list is not exhaustive, nor in any order of importance.

Weaknesses and Problems of Financial Metrics

However attractive to corporate managers, economic and financial metrics also have several weaknesses. These are summarized in Figure 13.

Figure 13
Weaknesses and Problems of the Economic/Financial Metrics

- Difficulties in measuring the outputs and the impacts of S&T.
- Difficulties in isolating precise impacts of S&T and allocating them to inputs to S&T.
- Complexity of the innovation process makes it very difficult to apply ROI or ROA techniques, mainly because the returns cannot be attributed to specific inputs.
- Unpredictability of the innovation activity may create technical successes but commercial failures, hence making it difficult to predict outcomes, and to use present value techniques.
- Inputs to commercial success (profits and other economic returns) are varied, thus making it difficult to isolate the effects of S&T.
- Existence of a "temporal gap" between the long-term nature of S&T, and the short-term objectives and the financial tools of corporate management.
- Overall industry-wide statistical correlations provide only circumstantial link between investments in S&T and economic benefits.

This list is not exhaustive, nor in any order of importance.

The weaknesses of financial and economic metrics are primarily in the difficulty to measure and to precisely isolate their impacts on the innovation process. Traditional financial indicators measure more definable phenomena of economic activity. The R&D activity lends itself much less to definition and to quantification—hence the shortcomings of using such indicators for R&D evaluation.[34]

Best Uses of Economic and Financial Metrics

Industrial Examples

Although economic and financial metrics are hardly the perfect means to assess R&D, they have nevertheless been used by R&D performing units and by their organizations. One key element in the will of organizations to utilize these metrics is their desire to assess the risk in the R&D activity. Hence, in addition to the usual concern for the economic assessment of specific investments and the activities they support, there was also the management aspect of dealing with such risk. Clearly, companies are well positioned to assess risky investment and have developed a pool of economic and financial measures for this task—some of which are also used in assessing R&D. The special case of the inventive process is its complexity, long-term, and other limiting attributes such as multiple inputs and multiple stages in its process.

The following are examples of how major industrial companies use economic and financial metrics for the assessment of their innovation effort. As seen below, in most cases companies utilize a mix of economic/ financial and other metrics in their evaluation effort. The level of importance of economic measures (compared with other metrics) varies among companies.

Union Carbide. The chemical company has used "project profiles" to assess its R&D at the project and program levels. The method is composed of a weighted score of the project, based on several criteria. Among them are costs, expected ROI, expected profits, and probabilities of technical and commercial success. The expected financial returns are computed in relation to the probabilities of success, which in turn are obtained by subjective evaluation performed by technical and business managers.

General Electric. Among the methods and metrics utilized by GE's R&D Center are the cost per patent and licensing income. The company used such data sets at the corporate level and to assess selected products, such as in medical diagnostics. But the company also used a discounted rate of return analysis of the R&D Center. This analysis was done by an external evaluator. The questions used in determining the financial returns included: (1) what was the total cost of the "technology" generated by the R&D Center? (2) What was the economic/financial benefits to the company? and (3) What was the proportion of inputs from the R&D center that contributed to the economic payoffs from the technology?

In this example the company evaluated actual technologies that "graduated" from the R&D Center, thus making the hindsight approach relatively simpler to quantify. Yet the external consultants based their estimates primarily on *subjective* information provided by those familiar with the technology and its R&D inputs and downstream impacts.

3M Corporation. The consumer products company evaluated its R&D effort by means of internal audits. These included assessment of a variety of programs, such as new product development, new processes, and technology-building programs. The 3M evaluators applied three categories of factors to rate the programs: technical, business, and overall factors. In the technical factors category they included the profitability of technical success. In the business category they used the "financial potential" of the program, measured in terms of potential sales and profits. These were attenuated by the factor of "probability of marketing success."

The company evaluated its own audit. On the positive side the audit helped management to predict with some accuracy the success or failure of the program. It also helped the R&D unit/laboratory to improve its effort and to better communicate with other R&D units at the 3M corporation.

Among the shortcomings of the audit, the company listed the expense of a specialized unit to continually collect data and conduct the audit, and the time and expense it takes on all parties involved in the auditing effort. Nevertheless 3M managers have generally expressed their overall satisfaction with the audits.

Conclusions

As Walter Robb of General Electric said: "If you knew in advance what the payoff would be, then it's not R&D."[35] The unpredictability of R&D (and S&T) makes any attempt to predict their economic payoff very difficult indeed. With the use of subjectively derived probabilities of both technical and commercial success, firms have tried to gain some crude estimates. Even in the case of *a posteriori* evaluation there are critical problems in first establishing the conceptual progression of R&D product commercialization to business benefit, then attributing that part of the success to R&D. The appeal of economic/financial measures has always been that they could relate to productivity, profits, sales, and such business variables. If, therefore, problems in conceptualization and measurement hinder such a relation, perhaps the solution, albeit partial, may lie in the strategy of the business.

Managers and many scholars argue for a closer link between R&D and the business/strategic objectives and plans of the organization. Yet, even in uncommon cases where such a link is strong, the element of risk embedded in R&D and S&T, combined with the unpredictability factor, combine to hinder assessments using financial metrics. So, what are the "secrets" to the use of these metrics? An illustrative list of factors that contribute to successful application of financial measures is given in Figure 17.

However partially successful, the use of economic/financial metrics has largely failed to accomplish the economists' mission to gain enough knowledge that would allow us to optimize the allocation of resources to R&D and S&T. Because of the complexity of the R&D activity and other factors listed in this chapter, the economic data are circumstantial and most correlations are the result of covariation of inputs and distantly related outputs.

So, as the productivity paradox has demonstrated, aggregated statistics for economic/financial measures are not viable. Alden Bean (1995) has made a succinct case for desegregated and process assessment of economic benefits.[36] He argued that "it is not just the R&D intensity that is important but how the effort is allocated across the spectrum of R&D activities" (p. 28).

Finally, there is one benefit from the use of financial measures to assess R&D and S&T. The psychological impacts of using quantitative and economic data and methods (or even attempting to do so) seem to be substantial. They raise the awareness of the R&D organization and its commercial entities to the costs of R&D and to its economic contributions.

WHAT R&D METRICS TELL US

Industrial companies evaluate their R&D activities for two complementary purposes: (1) to assess the contribution of the activity to their commercial objectives, and (2) to assess the efficient management of such activities as corporate operations. Although congruent, these two objectives require different metrics for their evaluation. In addition, the complexity of industrial R&D and the professional nature of scientists and engineers make matters even more difficult, because there is also a need to evaluate these human resources at different stages of the process.

Contributions to Corporate Success

The importance of industrial R&D is due to the impacts that its outputs have had on the economy and on society. Industrial companies generate the main body of innovations that are translated into new products and services, which then fuel economic progress and prosperity.

These far-reaching impacts of industrial R&D are reflected in the evaluation conducted by corporations. One of the purposes for evaluation is to assess the contributions of the R&D activity in the firm—to the commercial/business goals and outcomes. Figure 14 shows the use of key metrics of R&D in the measurement of such evaluation.

Figure 14
Illustrative Uses of Key Metrics of S&T in the Evaluation of the Contributions of Industrial S&T

METRIC	ILLUSTRATIVE USES
• **Economic and Financial**	• Correlation with sales & profits • Measures of ROI and ROA • Ratios of new product sales • Measures of cost-effectiveness
• **Bibliometrics**	• Measure of prestige
• **Mapping of S&T**	• Relation to marketing research
• **Patents**	• Stream of revenues from licenses • Relation to competitive position and market share • Ratios of sales and profits from patented new products
• **Peer Review**	• Project selection and allocation of resources • Overall contribution of IS&T
• **Process Outcomes**	• Stepwise contributions of innovations • Project selection & resources allocation

Not necessarily in any order of priority or importance.

Economic measures and patents are the most favored metrics used by industrial companies to assess the business contributions. In general, R&D is viewed by the firm as an investment, and patents are considered an acceptable and relatively easy to measure outcome from these investments. The quantitative attributes of these metrics make them more amenable to calculations and to comparison with other quantitative measures of corporate activities and outcomes (e.g., sales, profits, other investments).

A different set of criteria is used by corporations to assess the performance of their R&D in terms of contributions to processes and to the value chain. For example, in the new product development (NPD) process, companies assess the "time to market" as a goal to be achieved via the outcomes from R&D. This and similar corporate attributes are considered to be positive forces in the firm's struggle to sustain its competitive position in its market. Concepts such as "agility" are interpreted in the firm as enhanced ability to transform the outputs from S&T into viable new products that are ready for their markets.

But the key metrics are primarily used to evaluate the overall contributions to corporate success and performance. Expenditures for R&D and proximal outputs (such as patents) are the main form of measurement, via correlations with downstream business indicators (such as sales, profits, and market share). The process itself, and the attributes such as time to market, are usually implemented in the evaluation of the efficiency of operations.

The "Right" Metrics

So which of the metrics listed in this report are better measures of industrial R&D? The picture that emerges is that there are a variety of approaches by different companies. The choice of metrics depends on (1) the company's experience with R&D evaluation, (2) its mode of organization, (3) the power and influence of the business units, (4) the degree to which the customers for R&D have been clearly identified and construed within the corporate structure and processes for R&D, and (5) senior management's perception of what R&D does, how it contributes to the business of the company, and how it should be evaluated.

Is there a preferred or "best" approach and metrics to evaluate industrial R&D? The answer seems to be that all the metrics listed above are useful to some degree. Perhaps some metrics (such as bibliometrics and patents) are best in measuring one set of attributes that describe the R&D activity itself. Other metrics are better at measuring impacts of R&D on business. Through the link with business units and convergence with these units' strategies, it is thus up to the company to consider the available metrics, to weigh their usage against its needs and constraints, and to select the set that best fits its situation at the various stages of its innovation process.

WHICH METRICS AND WHEN TO USE THEM

The pool of R&D metrics described in this report includes bibliometrics, patents, peer review (judgmental), and economic/financial measures. Their usage depends on a variety of factors, some managerial, others organizational. In a study conducted by Geisler in the early 1990s, the most used economic financial metric by industrial companies was Return on Investment or Return on Asset. The findings from this research are shown in Figure 15.

Figure 15
Economic and Financial Methods for Evaluation of Research Used by Large Manufacturing Firms in the U.S. (N=23)

METHOD	No. of Firms Using(1) Original Study		Follow-Up		Frequency of Use(2) Original Study	Follow-Up
Return on Investment or Return on Assets	6	26%	11	48%	Annual	Annual
Cost-Savings	3	13%	8	35%	Annual	Semi-annual
Research-Return Ratio	1	4%	4	16%	Annual	Annual
Payback of Investment	1	4%	8	35%	Annual	Annual
Research Expenditures/Unit Sold	1	4%	3	12%	Semi-annual	Semi-annual
"Dollarization": Profit/ Cost of Research Employees	1	4%	4	16%	Annual	Annual
Match of Research Expenditures and Sales	3	13%	12	52%	Annual	Annual

OO.*Number of companies differs from sample, because of the use of multiple methods by some firms.*
42. *Average.*

The most popular non-economic metrics to evaluate industrial R&D were committees (peer review), on-time and on-budget accomplishments, and good achievements (milestones). These and other findings are shown in Figure 16.

Figure 16
Noneconomic Methods for Evaluation of Research Used by Large Manufacturing Firms in the U.S. (N = 23)

METHOD	No. of Firms Using[1] Original Study		Follow-Up		Frequency of Use[2] Original Study	Follow-Up
Committee Evaluation	21	91%	20	87%	Varies	Varies
On Time and On Budget	20	87%	22	95%	Periodical	Periodical
Goal Achievement	10	43%	12	52%	Periodical	Periodical
New Products and Processes	5	22%	11	48%	Annually	Annually
Improvements in Products and Processes	5	22%	18	78%	Annually	Annually
Innovation Break-throughs	13	56%	12	52%	Annually	Annually
Regulatory Compliance	4	17%	6	26%	Quarterly	Quarterly
Business Customer Satisfaction	1	4%	8	35%	Semi-annually	Quarterly
Contribution to Business Strategic Objectives	1	4%	14	61%	Annually	Annually

- *Number of companies differ from sample, due to use of multiple methods by some firms.*
- *Average.*

The literature falls short of advancing clear criteria as to when and in which circumstances one should apply specific metrics to evaluate industrial R&D. We do know that some factors tend to positively influence the successful application of metrics. These factors are summarized in Figure 17.

Figure 17
Factors That Seem to Influence the Successful Application of Economic/Financial Metrics to Evaluate S&T

- These metrics are used only as an approximation.
- These metrics are used in conjunction with other measures, such as peer-review and bibliometrics.
- Evaluation is conducted routinely, not a "one shot" activity.
- Evaluation results in reallocation of R&D resources to projects with greater potential commercial value; but *without* terminating or largely reducing basic research.
- There are active channels of communication between R&D and corporate managers on the objectives, process, and utilization of the metrics and the evaluation effort.
- Methodology and actual data collection are done by experts from outside the corporation.
- There is agreement on the use of deflators for net-present-value calculations.
- Benefits to be quantified are collected from downstream the innovation process
- Outputs (such as patents) are also used in addition to expenditures to assess the economic/financial benefits.

Not necessarily in any order of ranking. This list is illustrative. Success is defined as satisfaction of the organization (at the corporate level) with the metrics.

What companies want from R&D is help in dealing with external factors that are inherent in keeping the firm's competitiveness. The complexity of the company's external environment is such that there are many "stakeholders," each with its own needs, requirements, and expectations. The proposition that R&D in the company can and should primarily lead to shareholder value and increased net worth may be in line with prevailing theories of the firm, but it grossly underestimates the complex array of stakeholders.

Customers, regulators, cultural trends, and vendors exert their relative pressures on corporate management to satisfy these stakeholders' needs and to meet their expectations. To a degree, all of these factors are filtered through the reasoning of senior management. In some companies, the result of such compilation of data and diverse interests may be translated into technology policy and planning. But, in most companies, the resulting outcome is an informal agreement on what to expect from R&D and what should be the needs and requirements from it. At best, such needs and expectations are spelled out to a certain degree in the tasks assigned to the R&D function in the company, and may form a source of reasoning in creating criteria for selection of R&D projects and allocation of resources for R&D.

External factors account for the firm's overall need to maintain its competitive position in the marketplace, and to grow and expand. This is the link between R&D and strategy, advocated by many students of management of science and technology. Briefly, the link is based on the question: What is the role of R&D in the sustained success, growth, and survival of the company? Proponents of the notion of "alignment" or "integration" of R&D and strategy in the firm start out with the conviction that R&D indeed crucially impacts success, growth, and survival.

We know that simply having a workable pool of metrics does not by itself guarantee that these metrics will be applied, implemented, or successfully used by companies. As Figure 17 has shown, there needs to be a concerted effort of managers and R&D personnel to make such metrics work as acceptable evaluation tools.

CONCLUSIONS

This report described what we know about metrics of R&D. Several categories of metrics were discussed, as well as their strengths and shortcomings, and their best uses by industrial companies. We do know that having a pool of metrics does not by itself guarantee usage nor successful implementation. We also know that a single metric or category of metrics (such as bibliometrics or patents) cannot adequately nor sufficiently measure the outputs, outcomes, benefits, and impacts from R&D.[37]

We know that there are no precise recipes as to which metrics should be applied in which situations. We apply proximal metrics (such as bibliometrics) to the upstream components of the R&D process. Economic and financial metrics are better applied to the downstream stages, where commercialization of R&D is prevalent.

We know that, in addition to the judgment power of the peer review metric, we can also utilize quantitative metrics that measure the progress of R&D. Although these metrics offer only a partial view of R&D outcomes and impacts, they are nevertheless powerful tools that allow us to quantitatively evaluate R&D.

In conclusion, the array of available metrics to evaluate R&D makes the assessment process a feasible and meaningful activity. We have adequate metrics (or tools) to assess the outcomes and the performance of R&D—from the research components throughout the commercialization of its outputs and their transformation into products and services.[38]

REFERENCES AND NOTES

1. See, Jain, R. and C. Triandis, *Management of Research and Development Organizations*, 2nd edition (New York, John Wiley & Sons, 1997). Also see Rubenstein, A., *Managing Technology in the Decentralized Firm* (New York: John Wiley & Sons, 1989); and, Tipping, J., and E. Zeffren, "Assessing the Value of Your Technology," *Research-Technology Management*, 38(5), 1995, 22-40.
2. See, Kostoff, R., "Research Impact Quantification," *R&D Management*, 24(3), 1994, 207-218; and, Moser, M. and M. Plante, "Linking R&D with the Strategic Management Process of the Firm," *Engineering Management International*, 49(2), 1987, 127-132.
3. Gold, B., "Same Key Problems in Evaluating R&D Performance," *Journal of Engineering and Technology Management*, 6(1), 1989, 59-70. Also see Glass, E., "Methods of Evaluating R&D Organizations," *IEEE Transactions on Engineering Management*, 19(1), 1972, 2-11.
4. See, Rubenstein, A., and E. Geisler, "Evaluating the Outputs and Impacts of R&D/Innovation," *International Journal of Technology Management*, Special publication, 1991, 181-204; and Gold, B., *Research, Technological Change, and Economic Analysis* (Lexington, MA: Lexington Books, 1997).
5. Lach, S., and M. Schankerman, "Dynamics of R&D and Investment in the Scientific Sector," *Journal of Political Economy*, 97(2), 1989, 880-904.

6. Geisler, E., "The Cost of Research," *Engineering Valuation and Cost Analysis*, 2(2), 1998, 33-44. Also see Ito, K., and V. Pucik, "R&D Spending, Domestic Competition, and Export Performance of Japanese Manufacturing Firms," *Strategic Management Journal*, 14(1), 1993, 61-75.

7. See Geisler, E., *The Metrics of Science and Technology* (Westport, CT: Quorum Books, 2000).

8. See Rubenstein, A., "Setting Criteria for R&D," *Harvard Business Review*, 35(5), 1957, 95-104. More recently, see: Holbrook, J., "Basic Indicators of Scientific and Technological Performance," *Science and Public Policy*, 19(5), 1992, 267-273.

9. Garfield, E., *Citation Indexing* (New York: John Wiley & Sons, 1979).

10. See Narin, F., D. Olivastro, and K. Stevens, "Bibliometrics Theory, Practice, and Problems," *Evaluation Review*, 18(1), 1994, 65-76.

11. Nicholls, P., "Price's Square Root Law: Empirical Validity and Relation to Lotka's Law," *Information Processing and Management*, 24(4), 1988, 469-478.

12. Fruman, C., "Choices in R&D and Business Portfolio in the Electronics Industry: What the Bibliometric Data Show," *Research Policy*, 21(2), 1992, 97-124.

13. Koenig, M. and D. Gans, "The Productivity of Research Effort in the U.S. Pharmaceutical Industry," *Research Policy*, 4(4), 1975, 331-349. Also see Koenig, M., "Bibliometric Analysis of Pharmaceutical Research," *Research Policy*, 12(1), 1983, 15-36.

14. Cockburn, I. and R. Henderson, "Absorptive Capacity, Coauthoring Behavior, and the Organization of Research in Drug Discovery," *The Journal of Industrial Economics*, 46(2), 1998, 157-182.

15. See, for example, MacRoberts, M., and D. MacRoberts, "Problems of Citation Analysis: A Critical Review," *Journal of the American Society for Information Science*, 40(5), 1989, 342-349.

16. Evers, A., "A Review of New Developments in Text Retrieval Systems," *Journal of Information Science*, 20(6), 1994, 438-445.

17. Coulter, N. and I. Monarch, "Software Engineering as Seen Through HS Research Literature: A Study in Co-Word Analysis," *Journal of the American Society for Information Science*, 49(13), 1998, 1206-1223.

18. See, for example, Leydesdorft, L., "Why Words and Co-Words Cannot Map the Development of the Sciences," *Journal of the American Society for Information Science*, 48(5), 1997, 418-427.

19. See the extensive work on TDM by Ronald Kostoff at <http://dtic.mic/dtic/kostoff/index.html>.

20. Rubenstein, A., M. Glaser, and E. Geisler, *Evaluation of Outputs from R&D and Related Questions* (Chicago, Iasta Inc., 1980).

21. See Samuels, R., "Pathways of Technological Diffusion in Japan," *Sloan Management Review*, 35(3), 1994, 21-32.

22. See, for example, Barker, D. and D. Smith, "Technology Foresight Using Roadmaps," *Long Range Planning*, 28(2), 1995, 21-29.

23. See, Kopesa, A., and E. Sohliebel, "Science and Technology Mapping: A New Iteration Model for Representing Multidimensional Relationships," *Journal of the American Society of Information Science*, 49(1), 1998, 7-17.

24. See, for example, Harnad, S. (Ed.), *Peer Commentary on Peer Review* (Cambridge, Cambridge University Press, 1982).

25. Geisler, E. *The Metrics of Science and Technology(*Westport, CT., Quorum Books, 2000).

26. See Rubenstein, A., *Managing Technology in the Decentralized Firm* (New York, John Wiley & Sons, 1989).

27. Griliches, Z., "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature*, 18(4), 1990, 1661-1707.

28. See Taylor, C., and Z. Silberston, *The Economic Impact of the Patent System: A Study of the British Experience* (Cambridge, Cambridge University Press, 1973), and see, O'Donoghue, T., "A Patentability Requirement for Sequential Innovation," *Rand Journal of Economics*, 29(4), 1998, 654-679.

29. Crepon, B., and E. Duguet, "Estimating the Innovation Function from Patent Numbers," *Journal of Applied Econometrics*, 12(2), 1997, 243-263.

30. Cardon, J., and D. Sasaki, "Preemptive Search and R&D Clustering," *Rand Journal of Economics*, 29(2), 1990, 324-338.

31. Deutch, C., "Patent Fights Aplenty for MRI Pioneer," *New York Times*, July 12, 1997, Section 1, pg. 33.

32. Foster, R., "Estimating Research Payoff by Internal Rate of Return Method," *Research Management*, 13(3), 1971, 27-43.

33. Jaffe, A., "Technological Opportunities and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value," *The American Economic Review*, 76(5), 1986, 984-1001.

34. See Frantzen, D., "R&D Effort, International Technology Spillovers and the Evolution of Productivity in Industrial Countries," *Applied Economics*, 30(11), 1998, 1459-1469.

35. Geisler, E., *Creating Value with Science and Technology* (Westport, CT, Greenwood Publishing Group, 2001).

36. Bean, A. "Why Some R&D Organizations Are More Productive Than Others", *Research-Technology Management*, 38 (1), 1995, 25-29.

37. Funk, K., "Performance and Sustainability over the Long Haul," *Perspectives on Business Innovation*, 7, 2002, 62-66.

38. See Mansfied, E., "Intrafirm Rates of Diffusion of an Innovation," *Review of Economics and Statistics*, 45(3), 1963, 348-359; Geisler, E., *Creating Value with Science and Technology* (Westport, CT, Greenwood Publishing Group, 2001); and also Christensen, C., *The Innovator's Dilemma* (New York, Harper Business, 2000).