Database Requirements for Research Impact Assessment

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ABSTRACT

This paper describes the requirements for, and potential uses of databases in supporting research assessment and evaluation. It delineates the growing importance of research impact assessment. The paper shows how potential database utilization can improve identification of the indirect impacts of research, help map the structure and relationships among research areas, help improve the predictive reliability of research assessments, and help expand awareness of ongoing research during assessments. The final part of the paper discusses requirements for research which will improve the utilization of databases in research assessments.

IMPORTANCE OF RESEARCH IMPACT ASSESSMENT

In research sponsoring organizations, the selection and continuation of research programs must be made on the basis of outstanding science and potential contribution to the organization's mission. Recently, there have been increasing pressures to link science and technology programs and goals even more closely and clearly to organizational as well as broader societal goals. This is reflected in a number of studies [6, 7, 33], in the controversial National Institutes of Health strategic planning process, in the controversial statements by the previous National Science Foundation director about closer alignment with industry and other government agencies, and in conversations with numerous government officials.

In tandem with the pressures for more strategic research goals are motivations to increase research assessments and reporting requirements to insure that the increasingly strategic research goals are being pursued by proposed and existing research programs. The 1992 Congressional Task Force report on the health of research [6] stated, as one of its two recommendations, "Integrate performance assessment mechanisms into the research process using legislative mandates and other measures, to help measure the effectiveness of federally funded research programs."

According to the statement of Genevieve Knezo, a Congressional Research Service representative, at a 1993 research assessment colloquium, "The House Science Committee has asked the Congressional Research Service to develop some options for legislative language that might be included in the mandates of the agencies that they have responsibility for, which would require or in some way discuss the need for R&D to be evaluated. We are exploring that right now. We have a task force in Congressional Research Service composed of about twelve people who are surveying the agencies for which the Committee has responsibility. We are also surveying agencies outside the jurisdiction of the House Science Committee, DOD and NIH specifically" [19].

The Government Results and Performance Act of 1993 (Public Law 103-62) was passed on August 3, 1993. This Act provides for the establishment of strategic planning and performance measurement in the Federal government, and for other purposes. Not only will the Federal agencies be required to establish performance goals for program activities, but as the law states, they will be required to establish performance indicators to be used in measuring or assessing the relevant outputs, service levels, and outcomes of each program activity. Early meetings of the newly-established Federal Research Assessment Network [11] focused in part on the implications for research from the Act.

Due to increased international competition, and the trends toward corporate downsizing, parallel pressures exist for industrial research organizations to link research programs more closely with strategic corporate goals and to increase research performance and productivity. In tandem with the

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increasing governmental interests in research assessment stated above, there is considerable industrial interest in research assessment as well. As an example, the Industrial Research Institute (IRI), whose 260 member companies invest over $55 billion annually in R&D, has shown intense interest in measuring research performance and effectiveness. The IRI has commissioned one of its internal panels (headed by Dr. James W. Tipping) to research the field and write a position paper on measuring and improving effectiveness of R&D on company performance. According to Dr. Tipping, two roundtables on this subject have been held. They have been oversubscribed but limited to 50 companies [38].

When the above activities are integrated and placed into a mosaic, the obvious trend for the future becomes clear. The research sponsoring agencies will become more accountable to the Administration and Congress on the relationship between sponsored programs and strategic goals, and soon thereafter the research performers will become more accountable to the sponsoring agencies. In addition, the accountability of industrial research to the broader corporate goals will increase (as has been observed over the past decade), and improved methods of measuring research performance and productivity will be sought continually by industrial research organizations. It is therefore important that research managers and administrators in government, industry, and academia understand the assessment approaches which could be utilized to evaluate research quality and goal relevance, and that researchers gain an understanding of these evaluation approaches as well. For the readers interested in learning more about research impact assessment (RIA) philosophy and methodologies in use today, references [4, 24, 25, 26] are strongly recommended.

BENEFITS OF DATABASE UTILIZATION IN RESEARCH IMPACT ASSESSMENT

Focus of Present Paper

In generating the RIA papers cited above, the author performed extensive surveys of the research evaluation and assessment literature for the last three decades. The finding was that much material has been written on the three major research evaluation methods (Quantitative, Peer Review, Retrospective), although few of these methods other than peer review are widely used in practice. Very little, if any, material has been written about the potential contributions from sophisticated databases and accompanying analytical techniques to improved research evaluation and assessment. Thus, advances in the practice of research evaluation and assessment have proceeded slowly. A substantial improvement in research evaluation and assessment will therefore require at least the following two conditions. First, quantitative and retrospective techniques need to be implemented in the practice of research evaluation and assessment, probably in support of peer review. Second, a variety of databases and database analytical techniques need to be developed and implemented in practice as well to support research evaluation and assessment.

This paper addresses the second condition, and focuses on the requirements for databases/analyses in research evaluation and impact assessment. It addresses a variety of potential database applications, rather than examine and develop one concept in detail. It provides examples of the author's efforts in developing these different types of databases and analytical techniques for illustrative purposes. Its focus is on breadth of coverage, to stimulate the readers to do further R&D on either some of the concepts described or on novel concepts which could address the problems described.

Summary of Types of Benefits

Research is the pursuit and production of knowledge by the scientific method. Underpinning research is the generation, flow, synthesis, and interpretation of information. Central to the assessment of research is the capability to handle all phases of the information creation, flow, and integration cycle. The explosion of available information in the last decade requires the utilization of large databases to handle this information in support of research assessment.

In particular, sophisticated data collection, analysis, and interpretation schemes can track the dissemination of information flowing from research to other applications. A credible research product tracking scheme can help identify the indirect impacts of research more precisely, and can improve correlations between research evaluation predictions (such as peer review and bibliometrics) and downstream impacts.

Comprehensive databases describing sponsored research and development programs in many funding agencies and organizations, with sophisticated software to provide rapid access to the database contents, can help improve the selection, management, and evaluation of research programs. Research gaps can be identified, duplication of programs can be minimized, complementary and joint programs can be established, substantial leveraging of other agency programs can be implemented, and technology planning can be improved with better awareness of maturing research programs.

Tailored databases which contain information about the structural relationships among projects and programs can help identify critical paths for development in R&D programs. This is important in allocating resources among programs in mission- oriented agencies and other organizations.

Sophisticated algorithms for manipulating and interpreting large technical textual databases would allow pervasive themes of the databases to be identified, as well as the relationships among the themes and sub-themes. Low frequency anomolous relationships which could be important are identified easily with these techniques. The algorithms would also allow identification of the translations between research areas and technology areas in the databases, and would provide guidelines and roadmaps for increasing the efficiency of searching unfamiliar databases.

These algorithms, and subsequent analyses, have the potential of identifying emerging research and development areas contained within the databases but not readily discernable. The software can also help in taxonomy construction, with the taxonomy elements obtained 'bottom-up' from the database language, rather than top down using an authoritative directed approach. Many different types of taxonomies could be constructed from the full text database, and relationships among the different elements of the different taxonomies could be obtained. Finally, by looking at the changes in the structure of research fields over time, the impact of sponsoring organization intervention can be ascertained.

Indirect Impacts of Research

Overview

One major benefit from large database utilization would be identification of the diverse impacts of basic research. The impacts of basic research are pervasive throughout a technological society, but for the most part the impacts of basic research are indirect on technologies, systems, and end products. A major limitation of articulating the benefits of basic research has been the lack of data which could show the pathways and linkages through which the research impacts the intermediate or end products. For example, research in fundamental Physics underlies almost every technological advance made in recent history. Yet an assessment method which can explicitly show the pathways along whivh these Physics impacts evolve is nonexistent. A credible RIA of completed research would trace the dissemination of the research products through the many communication channels and would identify the multitude of near and long term research impacts (impact on other research fields, impact on technology, impact on systems, impact on education, etc.). Having this data would provide more substantive arguments for continuing to provide the necessary funds to those who control the allocation of research funds.

The cumulative indirect impacts of basic research are not accounted for by any of the retrospective approaches (of the impact of research on technologies or systems) published or in use today. Future retrospective studies should devote more effort to identifying indirect impacts of research to enhance the credibility of these studies. While indirect impacts of research are much more difficult to identify than direct impacts, and the data gathering effort is much larger and more complex, neglect of indirect impacts skews the results and conclusions relative to the value of basic research significantly. Use of some of the advanced computer-based technologies available today, such as the network approach described in the following section or citation analysis [32], could identify and document many of the pathways of the indirect impacts of research.

Network-Based Approach

A recent study [30] which examined impacts of research on other research and technology through direct and indirect paths using a network approach showed that the indirect impacts of fundamental research can be very large in a cumulative sense. This network based modeling approach would allow estimation of the direct and indirect impacts of a research program or collection of research programs. The research program impacts would be multi-faceted, including impacts on advancing its own field, on advancing allied fields, on advancing technology, on supporting operations and mission requirements, etc. The model proposed in [30] differs from any reported in the literature in that it reflects more accurately the different types of impact which basic research generates. A major feature of the model is inclusion of feedback from the higher development categories (e.g., exploratory development, advanced development) on the advancement of research.

Philosophy of Proposed Network Approach. Existing matrix-based research impact models [8, 16) are most useful for applied R&D concepts and utilize a **vertical impact structure (forward diffusion of knowledge) where the impacts of research flow forward only to the more advanced development categories (e.g., research——> development——> systems)**. The proposed model uses a structure of **lateral and backward diffusion of knowledge superimposed on the vertical impact structure (e.g., research——> research——> development——> research——> development——> systems)**. The proposed model accounts for the upward impacts of research (forward diffusion) allowed by the present models. It also allows one research field to impact another research field (lateral diffusion) and allows the higher development categories to impact research as well (backward diffusion).

For example, a matrix model approach could have a vertical impact structure path consisting of Physics (research) impacting Lasers (technology) impacting Beam Weapons (systems). The proposed network model would include this path, but many others as well, including Physics (research) impacting Lasers (technology) impacting nanoelectronics (research) impacting Controls (technology) impacting Beam Weapons (systems), and including Physics (research) impacting Lasers (technology) impacting Fluid Flow Visualization (research) impacting Helicopter Blade Design (technology) impacting Helicopters (systems).

The impact of much basic research, especially on the higher development categories such as systems development, proceeds through many indirect paths. A quantitative model of impact should have the capability of identifying the paths along which impact occurs and quantifying the impact along as many paths as is possible. The existing forward diffusion matrix-based models are severely constrained on the number and types of paths along which impact occurs. These models are not able to account for impact along **lateral diffusion** paths (e.g., research-research) or along **backward diffusion** paths (e.g., technology-research). The proposed model allows impact to occur along any of these paths, and thus includes many types of indirect impacts as well as direct impact.

Example: Differences between Matrix and Network Approaches. A simple example will show the difference in breadth of impact allowed between the proposed model and a leading existing matrix-based model [8]. Assume it is desired to compute the impact of a research project R on a technology project T. In the standard methodology, it is only necessary to examine ONE path from R to T. This is the path of direct impact, and the value of the impact is the value of the matrix element RT.

In the proposed methodology, R and T are two nodes in a fully connected network. All possible paths between R and T are examined when computing the total impact of R on T. Thus, the overwhelming **majority** of paths which contribute to the **total impact** of R on T are the **indirect impact paths**. The total impact of R on T is the sum of the link value products along **EVERY** path connecting R to T. Continuing the example above, R could be the Physics research node and T could be the Laser technology node. In the standard matrix approach, only the direct impact of Physics on Lasers is considered. In the proposed methodology, additional paths between Physics and Lasers, such as Physics impacting Fluid Dynamics research impacting Lasers or Physics impacting Solid State Materials research impacting Lasers, would also be considered.

For a graph with a large number of nodes N, there are approximately e*m! paths (ranging in length from 1 to N-1 links) connecting R to T, where m is N-2. In the pilot study performed to test the validity of the proposed model and overviewed in this paper, the graph that was used consisted of 15 research nodes and 27 technology nodes. For the pilot study graph, e*m! is approximately 10 to the 47th power. In this simple example based on the **small** pilot study grid, the proposed method could theoretically examine link value products along **47 orders of magnitude** more paths than does the standard method. In the actual pilot study, because of the rapid convergence of the link value product algorithm used, link value products were computed along all paths five links or less in length. This means that approximately m^4, or 2.5 million paths connecting R to T, were examined. This same order of magnitude differential holds between the proposed method and the other matrix-based methods which were examined before the proposed method was devised.

Of equal importance to the **quantitative** difference between the two methods is the **qualitative** difference. The proposed approach allows **full weight** to be given to those research projects which have **large indirect** impacts. Many of the fundamental research areas, such as Mathematics, Physics, etc., have substantial impacts on other research areas (as well as technologies), and these indirect impacts are not fully captured in the matrix-based methods. Since the fundamental research areas tend to have indirect impact on many research and technology areas, when the impact is summed over all research and technology areas, the **total impact of these fundamental research areas becomes substantial.**

For any organization with a substantial fraction of its budget in these fundamental research areas, a method that is able to capture the sizeable indirect impacts of basic research is important. For an advanced technology development organization, where the impacts of the work are more focused to specific technologies and requirements, the benefits of the proposed multipath approach may be less (although they will always be greater than those of the matrix approaches, since the proposed method examines all the paths in the matrix approach and many more as well).

The remainder of this section describes the proposed method, an overview of the preliminary pilot study that was performed to test the feasibility of the method, key lessons learned from the pilot study, and recommendations for an enhanced study.

METHODOLOGY

Creating Domains and Forming the Network. The research impact quantification methodology presented here displays the value of a given research program to advancing its own field, to supporting other research areas, to supporting technology, and to supporting mission requirements. The first step in the methodology is defining a domain of potential impacts. For example, if the impact of research on other research, technology, and systems is desired, then the three-level domain for the model would be research, technology, and systems. Each of these levelsis subdivided further into a number of categories.

As a specific example, in the two-level domain (research, technology) pilot study that will be overviewed, research was divided into 15 categories (math, physics, chemistry, etc.) and technology was divided into 27 categories (training, navigation, countermeasures, etc.). These categories had the property of being relatively non-overlapping, and were similar to categories being used by the Navy for management purposes at the time of the study. All 42 categories are represented level, but some narrative descriptions (principally, for the armed services agencies) are at the program level (where a program is a group of principal investigators). For applications where linkages between work units are important, program level narratives are more appropriate. The database presently resides on a desktop computer hard disk, but could be accessed directly from the data sources via Internet if appropriate drones and system architectures were installed. This latter architecture would allow the data which the user sees to be more current.

Two major types of studies have been performed with this database. The first is standard text retrieval searches to identify programs of interest, usually in categories defined by the end user. Two examples of recent applications of text retrieval searches were identified above. The second type of study (Database Tomography) involves computational linguistics techniques to extract information about the total database structure. These techniques include multiword phrase frequency analyses for identifying pervasive research thrust areas, and multiword phrase proximity analyses for identifying relationships among thematic research areas. These computational linguistics techniques were described further in the previous section on evaluating and mapping the structure of research. Database Tomography has been applied to assessing the structure of research in the Former Soviet Union based on aggregating discrete assessment reports, among other applications.

Improving Predictive Reliability of Research Assessments

There is little literature which provides the basis for predicting which research programs/proposals will have the desired downstream impact [2, 3]. For example, the relationship between a proposal's peer review score or a project's bibliometric rating and the downstream impact on an organization's mission is not addressed in published studies. One could raise the question, as many active researchers have, as to whether there is value to any of these assessment techniques, since their predictive value is unknown. Bornstein concludes, after an extensive survey of peer review validity and reliability, that: **"If one attempted to publish research involving an assessment tool whose reliability and validity data were as weak as that of the peer review process, there is no question that studies involving this psychometrically flawed instrument would be deemed unacceptable for publication [3]."** The credibility and predictability of these assessment techniques are ripe topics for research. A long term tracking system for research product evolution would be required to gather the necessary data. The system would require agreement and coordination from a number of the larger Federal research sponsoring agencies, and maybe from industrial organizations as well. While such a system would not provide absolute answers, since tracking of the informal modes of knowledge communication would be almost impossible, it would provide a much better picture of research impact and its predictability than exists now. With the present state of information storage and processing capabilities, research product evolution tracking is an idea whose time has come.

DATABASE RESEARCH REQUIREMENTS FOR RESEARCH IMPACT ASSESSMENT

There have been a number of valuable retrospective studies of the impact of research on technologies and systems (e.g., [9, 17, 18]). In these studies, crucial R&D events are identified which had a major impact on successful technologies and systems. In future studies of this type, more emphasis should be expended on identifying and tracing the pathways of the indirect impacts of research. Especially for basic research, the research products are disseminated broadly, impacting eventually not only the sponsoring organization's goals, but the broader societal goals as well. These broader impacts should be captured within the studies.

The latest technologies, such as information processing and computer hardware and software, should be employed in these retrospective approaches. Citation and co-citation analysis, combined with co-word analysis, could trace some of the indirect impact pathways. Citations of successive generations of papers, for example, could document the diffusion and dissemination of the products of research.

Alternatively, network approaches could explore the information flow among research and technology areas. Combined with co-nomination techniques, these approaches could not only shed light on information dissemination, but on the people involved in the diffusion process as well.

To fully understand a research program, especially in the assessment of that program, evaluators must be cognizant of the large body of research being conducted throughout the world. In addition, to fully understand the impacts of research on different technologies, evaluators must be cognizant of the large body of existing technology and technology being conducted throughout the world, and the existing and potential shortcomings in those technologies.

With the advent of high speed and high storage capacity computers, and advances in database software packages, the capability exists now to make large amounts of information available to researchers and evaluators. In particular, the capability exists to provide information about funded research and technology development programs being conducted throughout the world, as well as information about existing technologies. The author has discussed previously his multiagency research database which describes programs being funded by defense and non-defense Federal agencies. This database has been of immense help in assessing research programs, as well as helping to plan research programs. **However, a much larger and more comprehensive database, covering not only research but technology as described above, would be of substantial benefit to the research and technology performer community, the research and technology evaluation community, and the research and technology user community.** Such a database would involve the cooperation of many government agencies, and a number of industrial organizations as well. The requirements of, and planning for, such a database should be started in the near future.

Central to credible work in predicting and tracking the diffusion of information from research is a database of research products at various evolutionary stages which can feed the predictive models. This database of research products could be linked in part with the above-proposed database of research and technology. Since the research product evolutionary pathways transcend the research originating organization, and can intersect all societal sectors, the cooperation of many public and private organizations would be required to develop a database of research products in their evolutionary stages. Development and construction of such a database should start now.

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