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OPERATIONS RESEARCH AND THE RAND CORPORATION

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### BACKGROUND

As World War II was ending, a number of individuals both inside and outside the U.S. government saw the need for retaining the services of scientists for government and military activities after the war's end. They would assist in military planning, with due attention to research and development. Accordingly, Project RAND was established in December 1945 under contract to the Douglas Aircraft Company. The first RAND report was published in May 1946. It dealt with the potential design, performance, and use of man-made satellites. In February 1948, the Chief of Staff of the Air Force approved the evolution of RAND into a nonprofit corporation, independent of the Douglas Company.

On November 1, 1948, the Project RAND contract was formally transferred from the Douglas Company to the RAND Corporation. The Articles of Incorporation set forth RAND's purpose:

"To further and promote scientific, educational, and charitable purposes, all for the public welfare and security of the United States of America."

It accomplishes this purpose by performing both classified and unclassified research in programs treating defense, international, and domestic issues. The current staff numbers approximately 600 researchers and 500 support persons, with about 36% of the researchers being operations researchers, mathematicians, physical scientists, engineers, and statisticians. For most of its history, RAND's research departments have been discipline based (e.g., mathematics, economics, physics, etc.). However, recently the departments were reconstituted around five broad policy areas: defense and technology planning, human capital, international policy, resource management, and social policy.

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This article focuses on RAND's contributions to the theory and practice of operations research. However, RAND has also made major theoretical and practical contributions in other areas, including engineering, physics, political science, and the social and behavioral sciences.

#### **THE FIRST TEN YEARS (1948-1957)**

The first decade saw RAND accomplishments ranging from the beginning of the development of systems analysis, which evolved from the earlier more specific and more narrowly focused operations analyses, to the creation of new methodological concepts and techniques to deal with problems involving many variables and multiple objectives..

*Systems analysis* may be defined as the systematic examination and comparison of alternative future courses of action in terms of their expected costs, benefits, and risks. The main purpose of system analysis is to provide information to decisionmakers that will sharpen their intuition and judgment and provide the basis for more informed choices. From the beginning it was evident that to be successful, systems analysis would require the conception and development of a wide range of methodological tools and techniques. One of the most important sources of these tools and techniques was the emerging discipline of *operations research*.

In the early 1950's Edwin Paxson led the project that produced a report entitled *Strategic Bombing Systems Analysis*, which is generally regarded as the first major application of the concept of systems analysis, as well as the source of the name for the new methodology. Among other things, the report advocated the use of decoys to help mask bombers from enemy defenders. This study was a catalyst that stimulated the development and rise of a number of analytical methods and techniques. Some of the more important examples are:

- *Game theory*: Mathematics and game theory were prominent subjects in the early research agendas of Project RAND. Lloyd Shapley, J.C.C. McKinsey, Melvin Dresher, Martin Shubik, Rufus Isaacs, and Richard Bellman were among the numerous early RAND contributors to

this area. John von Neumann, who is often cited as the father of game theory, and Oskar Morgenstern, who linked game theory to economic behavior, were active RAND consultants, as were many others with connections to major universities.

- *Enhanced computer capabilities:* The Paxson project required computer capabilities beyond those available at that time. This stimulated developments that lead to the JOHNNIAC digital computer in 1954. Based on a design by John von Neumann, it was one of the six "Princeton class" stored programming machines and the first operational computer with core memory in the world. In the first on-line time-shared computer system (1960), RAND built the JOHNNIAC Open Shop System (JOSS), one of the first interactive programming languages for individual users.
- *Dynamic Programming:* The Paxson project also demanded the examination of the dynamic programming of key strategic bomber components (e.g. decoys) in the context of an overall enhanced strategic capability. This, along with the demands of other projects in the early 1950's, provided a significant part of the motivation for the development of the mathematical theory of dynamic programming. Richard Bellman, together with a few collaborators, almost exclusively pioneered the development of this theory. The first RAND report on dynamic programming was published in 1953. Bellman's well-known book (*Dynamic Programming*) followed in 1956, and his book with Stuart Dreyfus (*Applied Dynamic Programming*) was published in 1962.

A second large systems analysis study of this period was a study led by Albert Wohlstetter on the selection and use of strategic air bases. It developed basing and operational options for improving the survivability of SAC forces and helped shift the focus of strategic thinking in the United States toward deterrence based on a secure second-strike force.

Another major effort beginning in the 1950's that led to the development of operations research tools was research on logistics policy issues. RAND's involvement with Air Force logistics stressed the demand for spare parts and the need for logistics policies that could cope with demand uncertainty. Major players in this effort were Stephen Enke, Murray

Geisler, James Peterson, Chauncey Bell, Charles Zwick, and Robert Paulson. The key analytical issue here was the examination of alternative policy issues under conditions of strategic uncertainty. Early research used "expected value" analysis. Later, RAND researchers developed and used more sophisticated methods, such as:

- The use of sensitivity analysis to determine what areas of uncertainty really matter in final outcomes;
- Iteration of the analysis across several relevant future scenarios to seek problem solutions that are robust for several of the possible (uncertain) scenarios;
- Given the outcomes of the above, design R&D activities that will (1) reduce key areas of uncertainty, (2) provide hedges against key uncertainties, (3) preserve options for several possible courses of action, any one of which might be used when the future environment becomes less uncertain.

Finally, the first decade witnessed the development of a number of methods and techniques that were useful across a range of RAND projects and elsewhere.

Some important examples are:

- *Problem Solving with the Monte Carlo Techniques*: Although not invented at RAND, the powerful mathematical technique known as the Monte Carlo method received much of its early development at RAND in the course of research on a variety of Air Force and atomic weapon problems. RAND researchers pioneered the use of the method as a component of a digital system simulation.
- *A Million Random Digits with 100,000 Normal Deviates*: The tables of random numbers in this 1955 report have become a standard reference in engineering and econometrics textbooks and have been widely used in gaming and simulations that employ Monte Carlo trials. It is RAND's best selling book.
- *Approximations for Digital Computers*: This book, by Cecil Hastings and J.P. Wong, Jr., contained function approximations for use in digital computations of all sorts.
- *Systems Development Laboratory*: This laboratory was set up

under the leadership of John Kennedy to help examine how groups of human beings and machines work under stress. The work ultimately led to the formation of the System Development Corporation.

#### **THE SECOND TEN YEARS (1958-1967)**

This period in RAND's history witnessed the beginning of the evolution of systems analysis into policy analysis. It also witnessed the beginning of research on domestic policy issues.

One of the most important dimensions of change as systems analysis evolved into policy analysis was the context of the problem being analyzed. Contexts became broader and richer over time. What was taken as "given" (exogenous to the analysis) before became a variable (endogenous to the analysis) later. For example, in the typical systems analysis of the 1950's and early 1960's, many considerations were not taken into account very well, often not at all: e.g., political, sociological, psychological, organizational, and distributional effects. Thus, as systems analysis evolved into policy analysis, the boundaries of the problem space expanded. This had important implications for changes in concepts and methods of analysis. For example, with respect to models, the demands of the expanded boundaries of the problem space could not be met by merely trying to make models used in policy analysis bigger and more complex. Of equal importance, was the development of sophisticated strategies for the development and use of models.

While the evolution of systems analysis into policy analysis did not progress very far during this period, there are several areas of RAND research that were conducted in broader contexts than were typical of the 1950's. These included Ed Barlow's Strategic Offense Forces Study (SOFS), Bernard Brodie's work on the development of a strategy for deterrence in the "new" age of abundant nuclear weapons and ballistic missiles, Herman Kahn's analysis of civil defense in the event of a nuclear war, and Charles Hitch and Roland McKean's book *Economics of Defense in the Nuclear Age*, which espoused the view that the economic use of scarce resources should be a critical aspect of defense planning. This view was adopted by Secretary of Defense Robert McNamara and led to RAND's involvement in the development of the defense Planning, Programming, and Budgeting System (PPBS).

In addition to policy strides like those discussed above, the second ten years witnessed further development of methodological tools for quantitative analysis--primarily operations research tools. Major advances were made at RAND in the areas of mathematical programming, queueing theory, computer simulation, stochastic processes, and operational gaming.

Linear programming was probably RAND's most important and most extensive contribution to the theory and practice of operations research as well as to economic decisionmaking. Between 1947 and 1952, George Dantzig and others who worked in the Pentagon on the Air Force's Project SCOOT developed the simplex method and other basic features of LP. Dantzig moved to RAND in 1952. During the following decade, RAND was the world's center of LP developments. In addition to methodological developments by Dantzig and other RAND employees and consultants (e.g., the dual simplex algorithm), there was seminal work on classic problems like production planning and the traveling salesman problem. In addition, most of the pioneering programming of LP algorithms (e.g., the first code for the revised simplex method) was carried out by William Orchard-Hays and others at RAND. Much of the work of this period is captured in Dantzig's book, *Linear Programming and Extensions*, published in 1963 (which includes an extensive bibliography).

Seminal work in other areas of mathematical programming also took place at RAND during the 1950s and 1960s. Ralph Gomory developed the first integer programming algorithms; Philip Wolfe, George Dantzig, and Harry Markowitz initiated work on quadratic programming; and George Dantzig, and Albert Madansky initiated work on stochastic programming.

Three other examples of RAND work in the "tools" area during this period are worthy of note:

- *Simulation*. In the early 1960's, after doing complex simulation modeling "the hard way", Harry Markowitz and Herb Karr developed SIMSCRIPT, a programming language for implementing discrete event simulation models. This work led in 1968 to SIMSCRIPT II, which is still widely-used.
- *Artificial intelligence (AI)*. The man-machine partnerships explored in the Systems Research Laboratory gained new impetus as Allen Newell, Herb Simon, and Cliff Shaw began to construct a

general problem solving language that employed symbolic (non-numerical) processes to simulate human thinking on a computer. One of their initial efforts to carry out a "theory of thinking" involved programming computers to play chess. On a broader scale, this research resulted in several information processing languages (e.g., IPL V), which were similar to LISP and were used in some of the early AI computer work.

- *Flows in networks*. In 1962, Lester Ford, Jr. and Delbert R. Fulkerson, RAND mathematicians, published the first unified treatment of methods for dealing with a variety of problems that have formulation in terms of single commodity flows in capacity-constrained networks. Their book, entitled *Flows in Networks*, introduced concepts (e.g., "max-flow/min-cut") and algorithms (e.g., "out-of-kilter") that have been used to treat network problems ever since.

1964 saw the publication of the first of several RAND books by mathematician Edward Quade, who played a major role in developing and disseminating the methodology of systems analysis and (later) policy analysis. *Analysis for Military Decisions* documents an intensive five-day course that RAND offered to military officers and civilian decisionmakers in 1955 and 1959.

#### **THE THIRD TEN YEARS (1968-1977)**

This period in RAND's history saw an acceleration of many of the trends begun in the previous ten years. One of these trends involved the development of improved procedures for the use of expert judgment as an aid to military decisionmaking. The Delphi procedures grew out of this effort. These procedures incorporate anonymous response, iteration and controlled feedback, and statistical group response to elicit and refine group judgments where exact knowledge is unavailable.

Other trends involved the continued evolution of systems analysis into policy analysis and an increasing emphasis on analyzing major domestic research issues. Important in the last two trends was the establishment of the New York City-RAND Institute (NYCRI). Important RAND research efforts

during 1968-1977 include the work performed at the NYCRI and policy analysis studies for the government of the Netherlands.

#### **The New York City-RAND Institute**

In 1968, RAND began a long-term relationship with the City of New York to tackle problems in welfare, health services, housing, fire protection, law enforcement, and water resources. The NYCRI was formally established in 1969. The research staff evaluated job training programs, suggested solutions to shortages of nurses in municipal hospitals, helped change rent control, altered fire department management policies, reallocated police manpower, and helped improve Jamaica Bay's water quality.

The most successful of the NYCRI's projects was the one devoted to improving the operations and deployment of the Fire Department of New York. In 1968, the major problem facing the Department was the rising alarm rate. Its increasing workload was not significantly relieved by adding more men and equipment; nor were traditional methods of fire company allocation, dispatching, and relocation working. The Institute's studies altered the way the Department managed and deployed its men and equipment and operated its dispatching system. An integral part of the research involved creation of a wide variety of computer models to analyze and evaluate deployment, which led to the formulation of new policies. Warren Walker and Peter Kolesar were awarded ORSA's 1974 Lanchester Prize for a paper that described how mathematical programming methods were applied to the problem of relocating available fire companies to firehouses vacated temporarily by companies fighting fires. The entire body of work from this project is documented in [Walker, Chaiken, and Ignall, 1979].

#### **Policy Analysis Studies for the Dutch Government**

Reflecting an increasing interest in doing policy analysis studies in international contexts, RAND started working for the Dutch government in the 1970's.

One important study was concerned with protecting an estuary from floods. In April 1975, RAND began a joint research venture with the Dutch government to compare the consequences of three alternative approaches for protecting the Oosterschelde, the largest Dutch estuary, from flooding. Seven categories of consequences were considered for each alternative:

financial costs, ecology, fishing, shipping, recreation, national economy, and regional effects. Within each category, several types of consequences were considered. In June 1976, the Dutch Parliament adopted one of the alternatives based in large part on the results of the RAND study: to build a 10 km, multi-billion dollar storm surge barrier with large movable gates across the mouth of the estuary. The study required the development of sophisticated computer models of estuaries and coastal seas.

A second study was focused on improving water management in the Netherlands. Begun in April 1977, the Policy Analysis for the Water Management of the Netherlands (PAWN) project was conducted jointly by RAND, the Dutch Government, and the Delft Hydraulics Laboratory. It analyzed the entire Dutch water management system and provided a basis for a new national water management policy for the country. It developed a methodology for assessing the multiple consequences of possible policies, and applied it to generate alternative policies and to assess and compare their consequences. Considering both research and documentation, it directly involved over 125 person-years of effort. The project won a Franz Edelman Award for Management Science Achievement in 1984.

#### **THE FOURTH TEN YEARS (1978-1988)**

This period witnessed a number of major institutional milestones. Some examples:

- In 1982 the joint RAND/UCLA Center for Health Policy Study was funded by the Pew Memorial Trust. A year later RAND and UCLA established a joint Center for the Study of Soviet International Behavior.
- In 1984 a new Federally Funded Research and Development Center-- the National Defense Research Institute (NDRI)--was established, funded by the Office of the Secretary of Defense.
- The Arroyo Center, the Army's Federally Funded Research and Development Center for studies and analysis, was established at RAND in 1984.
- The Center for Policy Research in Health Care Financing, sponsored by the Department of Health and Human Services, was created in 1984.

These institutional developments helped RAND to enhance its work in existing areas of the research program--e.g., Health Policy--and to stimulate work in new areas--e.g., analysis of Army policy issues.

During this period, RAND's research program increased substantially in size and diversity. Many of the trends of the past continued--e.g., the increase in efforts devoted to domestic policy research and the tendency to conduct research in broader contexts. Several new trends began to emerge--e.g., an increase in emphasis on research done in international contexts other than the (then) USSR. The development of analytical concepts, methods, and techniques also continued. Some of the more important of these were:

- *RAND Strategy Assessment System (RSAS)*: Because of perceived limitations in methods of strategic analysis, in 1982 RAND began to develop methods for strategic analysis that combined classical gaming, systems analysis methods and techniques, artificial intelligence, and advanced computer technology. The RSAS provides a structure and tools for analyzing strategic decisions at the national command level as well as decisions at the operational level. It also provides great flexibility in choosing which roles are to be played by people and which by machines.
- *Dyna-METRIC*: The Dyna-METRIC logistics support model provided a major new tool for relating the availability of spare parts to wartime aircraft sortie-generation capability. The model, which was developed by Richard Hillestad and Irving Cohen, combines elements of queuing theory, inventory theory, and simulation. It is now an integral part of the Air Force logistics and readiness management system.
- *CLOUT (Coupling Logistics to Operations to Meet Uncertainties and the Threat)* is a RAND-developed set of initiatives for improving the ability of the Air Force logistics system to cope with uncertainties and disruptions of a conventional war overseas. The CLOUT initiatives are intended to offset the substantial variability expected in the demand for spare parts, maintenance, and other support activities, as well as the consequences of damage to theater air bases.

- *The Enlisted Force Management System (EFMS):* The EFMS project is notable for the scope and complexity of the decision support system that it developed, and for demonstrating how the tools of operations research can be married with emerging information technologies to provide real-time decision support throughout an organization. Warren Walker led a large RAND team that worked with Air Force counterparts beginning in the early 1980s. Together, they produced an organizational decision support system (ODSS) to help make decisions about the grade structure of the enlisted force, enlisted promotion policies, and the recruitment, assignment, training, compensation, separation, and retirement of Air Force enlisted personnel. Since 1990, the EFMS has been the primary analytical tool used to support major policy decisions affecting the enlisted force. The success of the system motivated the publication of a 1992 book, *Building Organizational Decision Support Systems*.

#### **CURRENT SITUATION**

After the first 40 years, most of the main trends outlined above continue to play themselves out--e.g., domestic research represents nearly 30% of RAND's \$100 million research budget, and methodological enhancements driven by the practical needs of the research continue to have high priority. In 1992, RAND established the European-American Center for Policy Analysis (EAC) in the Netherlands. Major research efforts so far have included studies of the safety of Schiphol Airport, ways of improving river dikes in the Netherlands while preserving the environment, and a systematic examination of alternative strategies for reducing the negative effects of road freight transport in the Netherlands.

See also: *Artificial intelligence, cost benefit analysis, defense analysis, Delphi method, dynamic programming, emergency services, fire models, game theory, gaming, inventory modeling, linear programming, logistics, military operations research, networks, nonlinear programming, optimization, public policy analysis, simulation, systems analysis, traveling salesman problem.*

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