OPERATIONS RESEARCH AND SYSTEMS ANALYSIS

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FOREWORD

One of the goals of the International Institute for Applied Systems Analysis is to increase the understanding of what systems analysis is and what it can do.

This paper, which was contributed by invitation to the Centennial Issue of *Science*, describes the genesis of systems analysis and gives a brief overview of the field, using examples to illustrate key points. Thus, it is designed to introduce systems analysis to a wide and varied audience.

Another paper contributed by an IIASA staff member to this special Centennial Issue of *Science* provides a brief description of some key findings of a mature and comprehensive systems analysis: Wolf Häfele, "A Global and Long-Range Picture of Energy Developments," *Science* 209:174–182, 1980. This paper has also been reprinted, as IIASA Research Report RR-81-8.

ROGER LEVIEN
Director

Operations Research and Systems Analysis

Hugh J. Miser

Operations research, unlike most sciences, is able to point to a well-defined combination of circumstances and events that not only began its activities as a coherent development but also caused its name to be coined. After Hitler rose to power in Germany, England sought to prepare a suitable defense against possible air attack, with the result that, by late 1937, the key elements of an effective defense had been devised: radar and the Hurricane fighter plane. But combining them into an effective system could not be left to improvisation, as the disappointing results of an air exercise showed in July 1938. Consequently, A. P. Rowe, then leader of the radar development work on England's east coast, proposed that research into the operational—as opposed to the purely technical—aspects of the

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radar-fighter system be undertaken, and the term "operational research" was coined to describe the work (*1*).

This new kind of research, conducted in close cooperation with the officers and men of the Royal Air Force, led directly to substantial improvements in England's air defense system, which was given its most decisive test in the Battle of Britain during August and September of 1940.

The success of this partnership between scientists and operating forces prompted the spread of operational research to other British commands and services. When the United States entered the war, this British precedent was pursued by U.S. military commanders, with the result that, by late 1942, groups of scientists were undertaking similar work for both the U.S. Navy and Army Air Corps. However, the name had been Americanized to "operations research."

By the end of the war, England, Canada, and the United States had employed perhaps as many as 700 scientists in work loosely described by these terms (*2*).

Some of the work that these scientists did merely exploited the technical backgrounds that they brought to their wartime tasks. However, there was also the important novelty that they had studied and evaluated the results of tactical operations, devised tactical innovations and predicted their possible consequences, and, when the innovations were actually used, compared expected results with those actually achieved. And this knowledge had often become the basis for helping with tactical planning, and even, during the later stages of the war, for contributing important knowledge to strategic choices.

History shows that operations research workers made important contributions to the war efforts of their countries. However, another outcome of this work was also important: Many of these scientists saw in their wartime scientific achievements the germ of a new science of operating man-machine systems that could be developed for peacetime activities and applied to their problems.

The Science of Operations Research

It is clear that many of these pioneers of operations research saw their work as being scientific; for example, as early as 1941 P. M. S. Blackett (a physicist who later won a Nobel Prize for his work on cosmic rays), in a memorandum on "Scientists at the operational level," emphasized that the work was "scientific analysis of operations" and should be staffed and carried out in the spirit of science (*3*). This memorandum had considerable influence on both sides of the Atlantic.

Many of the scientists who became involved with this wartime work were surprised to find that there were identifiable stabilities in situations that they had always considered to be totally formless. For example, consider the outcomes of air combat. While a commander can control his own tactics, he cannot control those of his enemy, nor can he eliminate uncertainty in the weather. Nevertheless, it was often possible to predict the outcomes with considerable accuracy (*4*).

The sense of wonder that such systems of men and machines operating in conflict in a natural environment could exhibit aspects of regularity was expressed by two of the most notable U.S. operations research pioneers, Philip M. Morse (a physicist from Massachusetts Institute of Technology) and George E. Kimball (a chemist from Columbia University), when they wrote in 1946 that "large bodies of men and equipment carrying out complex operations behave in an astonishingly regular manner, so that one can predict the outcome of such operations to a degree not foreseen by most natural scientists" (*5*).

Too, the World War II experiences had exhibited the classic cycle of the method of science (*6*). The scientists had observed nature (albeit the startlingly new phenomena of military operations), had built theories to account for these observations, had used them to predict future outcomes, and had tested these predictions against actual experience, with frequent agreement. Indeed, many of them had experienced several connected and successive cycles, from which had emerged fairly comprehensive theories with accepted predictive value. Thus, the novelty of wartime operations research did not lie in the method that was being used, but rather in the part of "nature" to which it was applied: military operations.

The consequence was a natural one: Many scientists expected that operations research could be extended to a wide variety of civilian peacetime operating systems. By the end of the first decade after the war, examples were available to give substance to this expectation (*7*), and by now their number and variety are very great (*8*). A recent example typifies much of what has been done.

Summary. The science of man-machine operating systems, which includes operations research and systems analysis, has achieved a substantial body of theory and application over the last 40 years. Its current strength prompts it to attack difficult large-scale problems while challenging the other relevant sciences to unite, not only with each other and operations and systems research, but also with society, to deal with some of the most widespread and important problems of our time.

In 1979 Eric Brodheim of the New York Blood Center and Gregory P. Prastacos of the University of Pennsylvania reported a notable study (*9, 10*) of blood distribution and utilization that they had conducted in response to a national problem (*9*).

> Each year over two million hospitalized Americans depend on the timely availability of the right type of blood products at 6,000 hospital blood banks (HBBs) in the United States. If the right blood products are not available . . . when required, then medical complications or postponements of elective surgery can result, which translate to extra days of hospitalization and expense. On the other hand, since most blood products may only be administered to a patient of the same blood type within 21 days of collection, overstocking at HBBs leads to low utilization, which increases costs and is wasteful of the scarce blood resource.

Thus, as Johanna Pindyck, director of the Greater New York Blood Program (the largest in the world), expresses it, "We face the major problem of how to maximize the availability of blood to each of . . . 262 hospitals . . . while effectively discharging our implicit covenant to our donors to see that their gift is efficiently utilized" (*11*).

Since there are approximately 200 Regional Blood Centers (RBC's) in the United States, Brodheim and Prastacos (*9*) viewed the problem from the RBC point of view, as well as from that of the HBB:

> Most blood products in the United States are derived from whole blood that is collected by an RBC in units of one pint from volunteer donors. After laboratory processing and testing, whole blood and blood products derived from whole blood are distributed to the HBBs, where they are stored to be available for transfusion when requested.
>
> The complexity of the blood inventory-management problem is due primarily to the perishability of blood, the uncertainties involved in its availability to the RBC, and the fluctuating demands and usages at the HBBs. Too, there are large variations in the sizes of the HBBs to be supplied, in the relative occurrence of the different blood groups, and in the mix of whole blood and blood products

used at each HBB. Finally, the performance of a regional (or hospital) blood-management system can be evaluated in terms of multiple criteria (or objectives), some of which conflict (e.g., availability vs. utilization of blood at an HBB), or involve costs that are difficult to estimate (e.g., the cost of unavailability).

As a result of this complexity, regional blood management systems have historically been decentralized and reactive in nature, characterized by the HBBs placing daily orders to bring their inventory to what each considered a safe value, and the RBC trying to fill these orders as they came, while keeping a necessary buffer in the stock. This created a feeling of uncertainty, as a result of which HBBs have generally tried to maintain high inventories of most of the 8 different types of each of these products in order to provide high availability to satisfy patient needs, and have accepted the low utilization resulting from spoilage. Consequently, the national utilization rate of whole blood and red blood cells prior to expiration was estimated to be only 80 per cent in 1974.

After studying the Long Island blood-distribution system, which was the test bed for their analysis, Brodheim and Prastacos reasoned that three important management concepts should be introduced into the approach they were exploring.

1) The institution of a regional management system to allocate the regional resources among the HBB's would increase the efficiency of resource utilization. This would call for some form of centralized decision-making at the RBC, which would operate under the objective of overall regional efficiency.

2) Some form of blood "rotation" would be required, whereby freshly processed blood would be sent to an HBB from which it might be returned some time later, for redistribution according to the regional strategy. Any regional strategy that allocates blood products to be retained until transfused or outdated would result in low utilization, especially in the case of the small-usage HBB's which, in aggregate, account for the largest part of overall blood usage.

3) It would also be desirable for a significant portion of the periodic deliveries to the HBB's to be prescheduled. In this way the uncertainty of supply faced by the HBB's would be reduced, with a resulting improvement in the planning of operations and the utilization of resources.

The blood needs of an HBB can be expressed as the demand (that is, the number of units required to be on hand for possible transfusion) and the usage (that is, the number of units actually transfused). However, from the RBC point of view, the effectiveness of the supply management can be measured in terms of two rates: the availability rate (that is, the fraction of days when the inventory of a given blood type on hand is sufficient to meet the demand) and the utilization rate (that is, the fraction of the supply that is transfused). The first task of the analysts was therefore to devise a model that translated demand and usage to availability and utilization rates as functions of RBC blood-distribution policies and HBB blood-stocking policies.

Since the availability rate at an HBB depends only on the pattern of demand and the inventory level, it could be explored on the basis of blood-bank data. The analysts found sufficient stability in the evidence to establish the "universal" piecewise linear relation between inventory level and mean daily demand, with the availability rate as a parameter, shown in Fig. 1. Tests showed that the ability of this model to predict was high. The availability rates that HBB managers considered to be adequate ranged usually from 85 to 95 percent.

The utilization rate depends on the size and age mix of the blood supply in an HBB, as well as the demand. The distribution strategy is also an important issue. After consultations with the HBB's, and in agreement with the management concepts outlined above, the following class of policies was chosen for analysis. Each HBB receives periodic shipments at intervals of 1 to 4 days (to be determined from the analysis, depending on the size of the HBB, and other considerations). Each periodic shipment to the HBB includes a number of fresh (or long-dated: 1- to 2-day-old) rotation units and a number of older (or stock-dated: 6- to 7-day-old) retention units. The latter are retained until transfused or discarded, but the rotation units that are in excess of a fixed desired inventory level at the end of the period are returned to the RBC for redistribution. Modeling this situation called for a finite-state Markov chain analysis.

Having derived these models to predict the HBB availability and utilization rates for any policy implemented by the RBC, the analysts examined the regional allocation problem, assuming that there were fixed penalty costs associated with nonavailable and nonutilized units. They found that the policy minimizing the total expected one-period cost was (i) to allocate all available retention units so as to equalize the utilization rates at all HBB's and then (ii) to allocate all available rotation units, which are not subject to spoilage while at the HBB, so as to equalize the availability rates at all HBBs.

It was shown that this policy is independent of unit penalty costs and that it maximizes both the availability and utilization of blood in the region simultaneously. That is, any deviation from the policy that would reduce utilization would also result in reduced availability for the next period, and vice versa.

The analysts also found that the short-term policy had the same structural characteristics as the policy that was optimal over the long run, and even that the utilization and availability rates calculated for the short term corresponded very closely to the optimal values for the long run. Thus, they could return to the result showing that the distribution policy list-

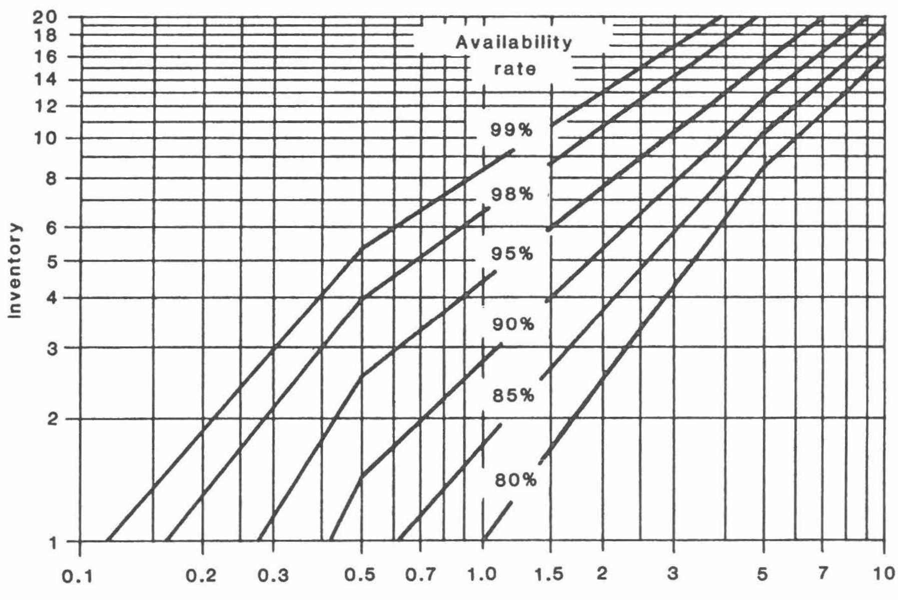

Fig. 1. Inventories and mean daily demands for blood units for given availability rates at hospital blood banks. [From Brodheim and Prastacos (*9*), courtesy of *Interfaces*]

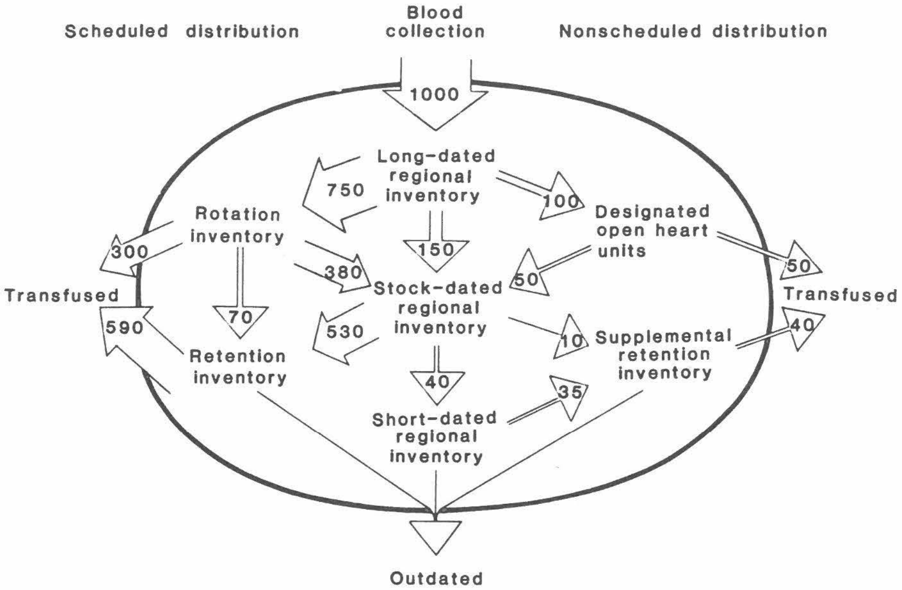

Fig. 2. Illustration of a planned regional blood flow. [From Brodheim and Prastacos (9), courtesy of *Interfaces*]

ed above for the one-period case was optimal, and they could establish the following principle (9):

> A distribution policy should seek to equalize utilization rates and availability rates among the HBBs in the region. This is also a policy that has the essential elements of "fairness" in spreading equally the nonavailability and nonutilization risks amongst hospitals regardless of their relative size, and is consequently a highly defensible policy.

With these results in hand, the analysts formulated the problem as a mathematical program, which they used to determine the appropriate distribution policy for the Long Island region. Figure 2 gives an example of such a policy.

The policy was then implemented in a sequence of planned steps, and was characterized by continuous interaction with the medical and administrative personnel, design of the necessary forms and procedures, educational sessions with the users, and development of an automated computer-based information system. The results were gratifying: utilization and availability of blood improved significantly and wastage and delivery costs decreased by 80 percent and 64 percent, respectively. The administrative system derived from these results (*12*) is being extended to the rest of the Greater New York Blood Program and is being considered for introduction elsewhere in the United States and abroad.

This example exhibits the pattern familiar to the wartime operations research analysts, and one that remains central to successful operations research work to this day: problem, observation, theory building (usually called modeling today), problem solution based on calculations from the theory, devising a system to be implemented, and testing it in actual practice, the analysts keeping in close touch throughout with the situation being studied and with the persons involved with it. To this may be added two aspects that this brief example did not treat: implementation brings new problems for analysis, and a changing underlying situation may call for revisions in the basic research.

The Methods

Almost all of the work during the war borrowed methods and theories from existing fields—mathematical analysis, probability, statistics, and the natural sciences—with only an occasional new model being assembled from these elements to represent the new aspects of nature that the analysts were exploring. The most notable exception was a theory of search developed as part of the work for the U.S. Navy (*13*).

The early postwar work followed the same pattern. Thus, it was hardly surprising that Philip M. Morse, in retiring from the office of the first president of the Operations Research Society of America in 1953, said that "one of our major tasks . . . is to develop analytic techniques and to broaden their range of application" (*14*). The operations research community's response to this challenge was to produce a rapid flow of theoretical developments that continues unabated to this day. Here it is possible to mention only important currents, relying on the reader to consult the new *Handbook of Operations Research* (*15*) for further elucidation and guides to important literature.

Some theories that already existed were extended significantly. For example, the theory of stochastic processes represented many systems of interest to operations research workers, who contributed to its development. The related theory of queues, which entered a mature period in 1950 owing to its extensive application in telephony, developed explosively, not only because of its mathematical challenge but also because of the widespread occurrence of queues in modern society and, therefore, in the systems studied by operations research workers. Optimal control theory, which advanced in response to operations research problems, value theory, which deals with what importance to attach to various possibilities, and game theory, which offered a challenging framework for thought about operational problems and choices, were all pursued energetically.

Operations research also produced new theories offering both significant intellectual challenge and important vistas of potential application. The best known of these is linear programming, which, like queuing theory, advanced rapidly in the three decades since the 1947 development of the simplex method by George B. Dantzig (who received the U.S. National Medal of Science in 1975 for his work in this field). The related fields of integer programming, geometric programming, nonlinear programming, large-scale programming, and stochastic programming also developed in response to needs in applications. The concept of decision assumed considerable importance early in the history of operations research, and a theory of decision now deals with such difficulties as those that arise when multiple and competing criteria are present. Dynamic programming is applicable to many kinds of sequential decision problems; the theory of flows in networks has a wide variety of applications; the theory of simulation is important for problems where analytic theories are cumbersome or inaccessible but where practical imperatives push the analyst to results; and the art of heuristic problem-solving is playing a growing role in handling problems of high computational complexity (*16*).

Arenas of Application

As operations research workers have dealt with the problems of business, industry, and government, they have observed many conceptual strands common to various operational processes. Thus, they have assembled groups of methods and models appropriate to many common functional processes, including production planning, inventory control, facilities location and layout, scheduling and sequencing, project planning and control, reliability, maintenance and replacement, marketing, human resource management, and forecasting (*15*, vol. 2). The *Handbook of Operations Research* devotes chapters (*15*, vol. 2) to eight arenas of application (urban services, health services, educational processes, transportation systems, military systems, electric utilities, the process industries, and the leisure industries), but the list can easily be lengthened to include banking, advertising, university administration, state and local government, federal govenment, highway safety, communication system management, agriculture, library and information system management, mining and the mineral industries, forestry and forest products, and many more (*17*).

The concerns of business and industry—and of management generally—are conspicuous in these lists, which explains why much of the work is carried out and reported under the rubric of "management science." However, only a stickler for fine detail would trouble to distinguish management science from operations research by more than the practical context of the work (*18*).

Lest the preceding discussion suggest that operations research can flourish only in big institutional contexts, let us turn to an issue of local governmental concern: a school desegregation issue in a community of modest size.

In 1954 the Supreme Court of the United States ruled that segregated schools for black and white children were an unacceptable form of public education and that schools should begin admitting students without racial discrimination "with all deliberate speed." A 1968 decision had the effect of speeding up the process of desegregation, and, to this end, it gave federal courts the authority to order busing school children as one way of achieving the desired goal.

In addition to arousing a storm of social and ethical issues, these landmark decisions presented school boards and school officials with two practical difficulties.

1) What, in quantitative terms, did the court mean by desegregation? Must every school have the same distribution by races as the regional population? Or is there some maximum allowable variation? The decisions did not deal directly with these questions, so the only course open to a school jurisdiction was to devise a plan, calculate the resulting school population distribution, and then submit it to the court to see whether or not it would win approval.

2) The practical difficulties of school and bus assignments are formidable, particularly if the numbers of schools and students are large, and if such constraints as restricting the amount of additional travel for students are considered.

When members of the school board of Alachua County, Florida (in which Gainesville is located), faced these difficulties, they obtained the assistance of Peter C. Belford and H. Donald Ratliff of the science faculty at the University of Florida in Gainesville. These two investigators approached the first of the two difficulties in this way, as explained in a 1971 account of their work (*19*):

> In order to get some feel for what the courts consider to be "acceptable" desegregation plans, we contacted a number of organizations, including the Department of Health, Education and Welfare and the National Association for the Advancement of Colored People, requesting any available information concerning desegregation plans that had been submitted to the courts for approval. In every case these organizations were either unable or unwilling to provide this information. We were finally able to obtain from individual school districts ten plans that had been accepted by the courts since 1967. These plans were from school districts in Alabama, California, Florida, and Georgia, and were approved by several courts.
>
> Since the courts did not give reasons for accepting these plans, an attempt was made to determine empirically from them some quantitative measures of acceptability upon which future plans could be based. Two measures that seemed reasonable were the maximum allowable deviation from the actual percent black in a given district, and the average allowable deviation from the actual percent black in a given district. Since a number of the plans had at least one school that was almost all white or almost all black, the maximum deviation provided little information.

The available information on the deviation that would be allowed for a given school from the actual percentage of blacks in a given district showed figures as high as 34 percentage points for schools with more blacks than the district average and 24 points for schools with fewer blacks than the average. However, it appeared, when the court decisions were viewed over time, that the allowable deviations from the district percentage of blacks were decreasing. Therefore, the school board of Alachua County, with this trend in mind, decided arbitrarily to seek a plan that would keep the percentage of blacks within 5 points on either side of the district percentage of 30 (in other words, each school would be required to have between 25 and 35 percent blacks), a decision that would yield an average deviation from 30 percent of somewhat less than 5 points, a figure small enough to appear likely to gain court approval.

The next step was to consider the problem of assigning students to schools to meet the desired objective, plus other problems such as keeping the additional distances traveled by students down to acceptable levels. For this purpose the analysts constructed a model of the situation. The school district was divided into a large number of student locations, each of which may be thought of as being the size of one block and the location of a school bus stop. For each location the analysts knew the numbers of white and black students living there and their current grade assignments, and the distances from the location to each available school in the district by the most direct routes.

The numbers of white and black students from each location that had to be assigned to each school were then determined under these restrictions:

1) Each student was to be assigned to exactly one school.

2) Each school was to have assigned to it a number of students equal to its capacity, which was known in advance.

3) The proportion of black students assigned to each school was to be between 25 and 35 percent of its capacity.

Some desirable features were also added:

4) No assignment would be made that caused a student to be bused more than 10 miles from home to school.

5) Any student who lived within 2 miles of an appropriate school would not be bused at all—he or she would walk.

And, of great importance:

6) Assignments would be made so as to minimize the total number of student-miles traveled.

Some transformations of this formulation allowed it to be recognized as a minimum-cost flow problem in a single-commodity network, for which there is not only adequate theory but also several efficient methods of computation.

The desired number of students in each school and the desired bounds on the number of black and white students in each school were provided by the superintendent's office. Each school district was designated as either an elementary school (kindergarten through fifth grade), a middle school (sixth through eighth grades), or a high school (ninth through twelfth grades). Each system was then treated independently.

For the elementary school system

there were 6887 students (of whom approximately 30 percent were black), 298 student locations, and 11 schools. The computed results for this system were:

- Percent black: 25 (four schools), 29, 33, 34, 35 (four schools).
- Average number of miles traveled by the 2005 bused students (of whom 944 were white and 1061 black): 6.
- Total number of student-bus-miles: 11,628.

Similar results were obtained for the middle and high schools. Figure 3 shows how the student locations were assigned to the three high schools.

The desegregation plan generated by the model was used as the basis for rezoning the schools in Gainesville; while some minor changes were made by the school officials, the final districts put into operation were almost indistinguishable from those derived by the computer (*20*).

As quite often happens, this study shed some light on other issues, notably the concern of the public that busing to achieve integration would involve students in long, time-consuming rides. However, a supplementary analysis showed this fear to be largely without substance. A comparison of the desegregation assignment with an optimal assignment of students to schools without regard to race showed that the racially balanced assignment increased the student-bus-miles by only 20, 6, and 7 percent for the elementary, middle, and high schools, respectively. "The results indicate that the actual increase in busing is much less, at least for the Gainesville system, than one might anticipate" (*19*).

Systems Analysis

Since the brief account of the wartime work in operations research showed how the work began in tactics but grew into planning and strategy, it is natural to look for a similar pattern in postwar work. The two examples already sketched deal with tactical work but must not be read to suggest that only tactical work has been done. Rather, the wartime pattern has been followed: solid foundations in tactical understanding have led to involvement in planning and strategy in many arenas (notably in defense and large corporations, but with instances of successful involvement in many other contexts as diverse as local government and university management).

However, it has been evident that each system worked on is merely a subsystem in a larger system—indeed, one of an ever widening congeries of systems. Thus, just as the radar-fighter system was part of a larger warfare system for the defense of England, so the regional blood-collection and -distribution system supports the hospitals of its region, which are a part of the nation's health care system; and the school-busing system for Gainesville is a supporting subsystem in the educational system for this city.

Consequently, the purposes of the subsystems are subservient to the purposes of the larger systems of which they are parts. For example, the school-assignment study aimed to use the buses to achieve a rough equality of the proportion of blacks in each school, the equal-proportion objective being an expression of a goal of the social system in which the school system was embedded. Similarly, the objectives the analysts adopted of having the students within 2 miles of their schools walk there and of limiting any bus ride to less than 10 miles are quantitative interpretations of social goals perceived to be held by the community. For the busing system to contribute to the goals of the larger system of which it is a subsystem, it has to operate somewhat "inefficiently," if we interpret efficiency as the subsystem objective of getting the students to school with a minimum of travel.

The success of operations research workers in developing scientific theories describing important classes of phenomena occurring in man-machine operating systems and in using these models to solve problems arising in these systems has inevitably driven them to study larger and larger systems or, in other words, to what is now called "systems analysis" (*21*).

But this imperative arises because it is intrinsic to the problems that society has, and the ways they are embedded in large systems. For example: our highway traffic system combines drivers and passengers, pedestrians, roads, vehicles, the customs and rules of the road, the weather, the surrounding environment, and the energy sources that make it work; our energy system includes the sources from which we derive energy,

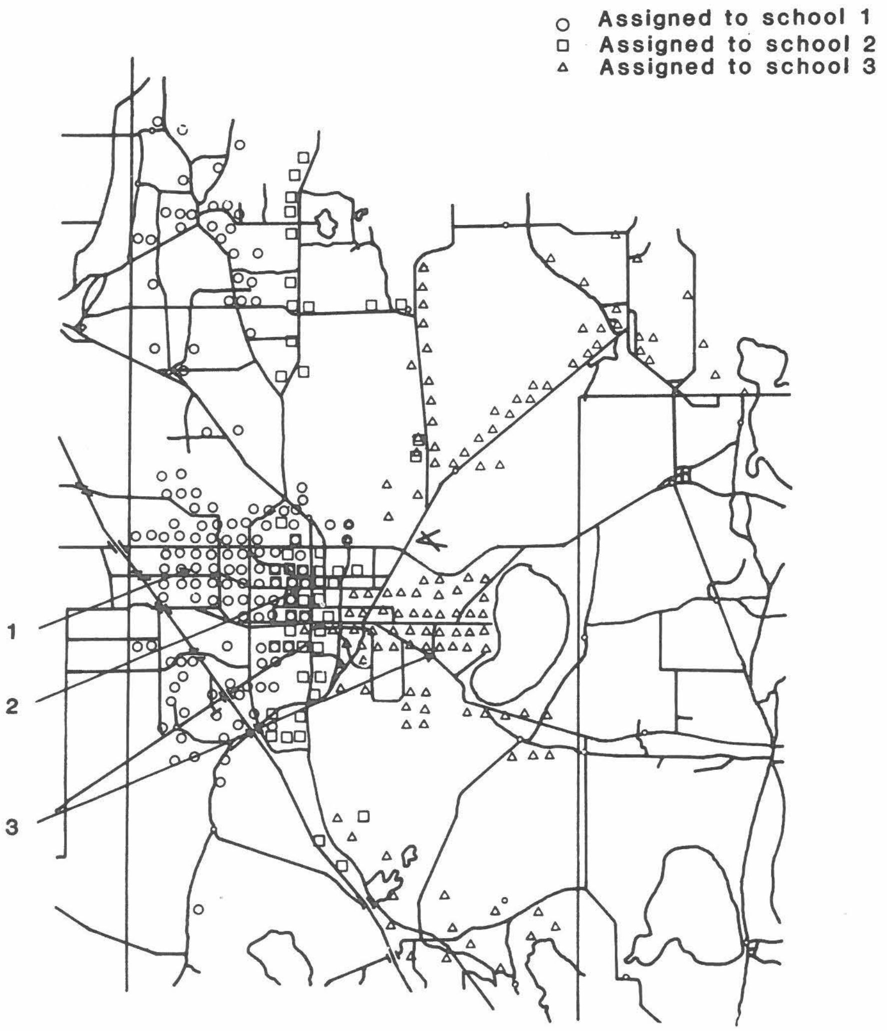

Fig. 3. Assignment of student locations to schools for the high schools of Gainesville, Florida. [From Belford and Ratliff (*19*), courtesy of *Operations Research*]

the means for converting these sources to usable forms, the distribution devices and procedures, the using community (including the highway traffic system), the political and international environment that affects energy deliveries and costs, and the natural and economic environment in which energy is used (and that is affected by energy use); the analyst concerned with air quality must study a system consisting, not only of the atmosphere and the natural global and terrestrial features that affect its behavior, but also of the patterns of human activity (including both transportation and energy use generally) that contribute to the deterioration of air quality; and so on.

As the operations research analyst is driven toward considering the operations of these larger systems, his classical partnership with the operators of the smaller subsystems (the managers of the RBC's and HBB's, for example) has to be extended to include, not only operating and policy officials with much larger purviews, but also scientists with other specialties relevant to the problems. For example, a comprehensive study of an air quality issue could demand not only operations research analysts and meteorologists but also demographers, economists, statisticians, chemists, energy systems engineers, and regional planners—in addition to the appropriate officials who should also participate in the work.

Thus, although historically systems analysis emerged largely from the early operations research work, as it is conducted today it is highly interdisciplinary. However, to reach its highest goals it must be pandisciplinary in the sense of combining the contributions of the various supporting disciplines into new syntheses—in other words, into new science explaining the behavior of the large systems it is studying.

Since major systems analyses are nearly always closely associated with major institutional policy decisions (*22*), the reports that describe them often do not find their way into the archival literature of science. Complete treatments are always too long for the usual journal article, and book-length treatment is somewhat deterred by the context of much of the work. Nevertheless, the literature is accumulating, both to describe case studies and to provide overviews of how such work is done (*23*). This literature shows that systems analysts expect a reasonably comprehensive systems analysis to:

1) Marshal both the evidence relating to the problem and the scientific knowledge bearing on it, and when necessary to develop new knowledge.

2) Examine critically the social purposes—of both persons and institutions—relating to the problem.

3) Explore alternative ways of achieving these purposes and, frequently, to design or invent new possibilities.

4) Reconsider the problem in the light of the knowledge accumulated during the analysis.

5) Estimate the impacts of various possible courses of action, taking into consideration both the uncertain future and the organizational structures that must carry these courses of action forward.

6) Compare the alternatives by applying a variety of criteria to the consequences.

7) Present the results of the study to all concerned in a framework suitable for choice.

8) Assist in following through on the actions chosen.

9) Evaluate the results of implementing the chosen courses of action.

The listing of these steps in order does not imply that they take place in this order in a systems analysis study. Rather, there is almost always a great deal of recycling of ideas and analysis; for example, the impacts of the chosen courses of action may dictate reconsidering the social purposes, the analysis of the chosen alternatives may generate new and more interesting ones for consideration, and so on. Nor do all systems analyses carry out all of the steps; only some may be needed by the user. Since the world does not stand still while the work is going on, its changes may dictate major changes in content and approach or, since user representatives must work with the analysis team throughout if the work is to be effective, early results may get translated into action or policy quickly. All of these influences may change the pattern of the work.

However, the central goal of the systems analyst is to bring results to bear on the functions of complex operating systems in society with a view to improving them; he helps those with relevant interests and responsibilities to change these functions beneficently. His analysis activities are aimed at assuring himself and others, to the extent possible, that the changes will have desired results. But these goals must be pursued under important limitations and difficulties:

1) Even though the analyst may dream of considering a system so large as to include within it all of the factors important to the problem, more practical considerations may require that reasonable boundaries be set so that the work can be completed and reported on a schedule that will make its findings effective.

2) The system under study is tied to an ongoing process of some sort in society that cannot be isolated for analysis and, therefore, must be dealt with in vivo, with many conflicting vested interests watching the analysis and its results. Since this setting denies the analyst the privilege of a secret burial of any mistakes that may be made, one of the hallmarks of systems analysis today is a literature of strong criticism (*24*), good for the progress of the field but perhaps misleading in its net public impact.

3) Further—and perhaps most unsettling from the current conservative view of science and its role in society—the analyst must work as a part of a system that his results may change.

What can be said, then, of the current state of the science of man-machine operating systems? It is well founded, active, and growing in size and importance (*25*). The cornerstone science of operations research has advanced to a state of significant maturity, with its underlying theories advancing, the scope and variety of problems it deals with expanding, and the effectiveness of its findings growing in importance. However, systems analysis, still in an earlier, more formative stage of development, faces several difficulties. The first concerns the scale of effort and institutional support. Clearly, if large-scale problems are to be tackled with interdisciplinary teams, such teams must be available, and there must be administrative arrangements that enable them to work together closely, conditions that seldom exist today, even in large U.S. government bureaus (*26*). However, there is a notable exception on the international scene that should be mentioned: the International Institute for Applied Systems Analysis in Laxenburg, Austria, a nongovernmental research institute founded in 1972 and today supported by 17 countries from both East and West, brings together scientists from more than 20 countries to conduct analyses on important international problems, such as those of energy and food.

The second difficulty concerns access to problems and the information bearing on them. To the worker in a classical science this may seem surprising, and it may be useful to recall, as an example, the number of institutions and administrations involved with energy problems. All of them have information that may be relevant to a systems analysis and many of them may have to be influenced by the results, if the findings are to be effective.

Unless there is cooperative access and active participation in the work—sometimes forthcoming and sometimes not—the systems analysis may be handicapped, or rendered useless.

The third difficulty relates to the U.S. science establishment's widely held philosophy of science. This philosophy, epitomized by the dichotomy "pure" and "applied" science, is quite inadequate for systems analysis, which clearly is inseparably both, in the best traditions of science's long history.

The last difficulty is the lack of a code of good practice, widely accepted by both the public and the community of science, to guide science's attempts to influence public policy and to give the public a fair and realistic concept of what to expect from science and systems analysis (*27*).

The Challenge of Systems Analysis

The urgency for developing systems analysis arises from the imperatives of society's problems: they call for the sort of approach that systems analysis represents. It is in the name of these urgent social problems that systems analysis extends its challenge to all of science. The problems to be addressed are some of the most important of our age and involve systems for which our thoroughly inadequate understanding must be improved, an improvement to which all sciences will be called on to contribute.

The work of operations research analysts, even in the short history of their subject, assures us that the difficulties to be overcome by systems analysis are intrinsic and important and will call forth the greatest scientific ability and ingenuity; the result will be important new science and significant applications. Since the goals and objectives of society and its subsystems are essential ingredients in a systems analysis, the spokesmen for these ideas (our literary men, political leaders, and philosophers) must become involved, thus offering science the naturally created opportunity—indeed, the obligation—of forming a union, not only of the sciences, but also with the arts, in the common enterprise of improving the lot of mankind.

The commonly accepted philosophy of science today must expand and mature to encompass systems analysis activities as an expression of scientific work. Leading thinkers in this field today (*28*) assure us that this is a natural extension of the classical activities of science and its philosophy, as well as a reasonable outgrowth of the philosophy of science as it has been developed in recent years.

Many of the operations and systems research workers in the United States gather at the semiannual joint meetings of the Operations Research Society of America and the Institute of Management Sciences. In addressing one of these meetings on 16 October 1979, Herbert A. Simon, who won the 1978 Nobel Prize in economics, hailed it as "a celebration of human rationality." The challenge to science and society is to enlarge this celebration to include the rational management of all of society's systems and their problems.

References and Notes

1. For a brief authoritative account by a participant, see H. Larnder, in *Operational Research '78*, K. B. Haley, Ed. (North-Holland, Amsterdam, 1979), p. 3.
2. For a condensed account of the early events in this spread of activity, together with references to fuller treatments, see H. J. Miser (*15*), vol. 1, p. 3.
3. This memorandum is included in P. M. S. Blackett, *Studies of War: Nuclear and Conventional* (Hill and Wang, New York, 1962), p. 171.
4. Although most of the military operations research in World War II dealt with air and naval operations, ground combat can also exhibit aspects of regularity. For example, the battle for Iwo Jima in 1945 progressed in accordance with a simple theory; see J. H. Engel, *Oper. Res.* **2**, 163 (1954).
5. P. M. Morse and G. E. Kimball, *Methods of Operations Research* (National Defense Research Committee, Washington, D.C., 1946), p. 7; also published by Wiley, New York, 1951.
6. As described in J. G. Kemeny, *A Philosopher Looks at Science* (Van Nostrand Reinhold, New York, 1959), especially chap. 5.
7. For accounts of early work in agriculture, retailing, and automobile traffic now regarded as classic, see, respectively: C. W. Thornthwaite, *Oper. Res.* **1**, 33 (1952–1953); H. C. Levinson, *ibid.*, p. 220; L. C. Edie, *ibid.* **2**, 107 (1954).
8. See, for example, the issues over the last decade of the journals *Operations Research*, *Management Science*, *The Journal of the Operational Research Society*, and *Interfaces* (this last being an especially rich source of business examples).
9. See E. Brodheim and G. P. Prastacos, *Interfaces* **9** (No. 5), 3 (1979).
10. At the 1 May 1979 meeting of the Institute of Management Sciences and the Operations Research Society of America in New Orleans, this work (*9*) received the eighth annual Management Science Achievement Award sponsored by The Institute of Management Science (TIMS) College on the Practice of Management Science. The quotations are from this paper for the most part, but some were adapted from a personal communication with G. Prastacos (his assistance in this regard is gratefully acknowledged, as is the permission from *Interfaces* to use the material from this journal).
11. The quotation from J. Pindyck is from a letter included in Brodheim and Prastacos (*9*).
12. See G. P. Prastacos and E. Brodheim, *Manage. Sci.* **26**, No. 5 (1980).
13. For an introduction to search theory and its literature, see B. O. Koopman, *Am. Math. Mon.* **86**, 527 (1979).
14. P. M. Morse, *Oper. Res.* **1**, 164 (1952–1953).
15. J. J. Moder and S. E. Elmaghraby, Eds., *Handbook of Operations Research*, vol. 1, *Foundations and Fundamentals*, and vol. 2, *Models and Applications* (Van Nostrand Reinhold, New York, 1978).
16. For some of the more recent work on heuristic techniques, see G. Cornuejols, M. Fisher, G. Nemhauser, *Manage. Sci.* **23**, 789 (1977); and R. Karp, *Math. Oper. Res.* **2**, 209 (1977). These two papers shared the 1977 Lanchester Prize of the Operations Research Society of America. For earlier references, see H. A. Simon and A. Newell, *Oper. Res.* **6**, 449 (1958).
17. The program of any recent semiannual joint meeting of the Operations Research Society of America (ORSA) and TIMS offers an instructive view of the current concerns and activities of the profession.
18. Indeed, the U.S. societies representing the two communities of interest, ORSA and TIMS, now hold their semiannual meetings jointly, share several publications, and have many joint activities.
19. P. C. Belford and H. D. Ratliff, *Oper. Res.* **20**, 619 (1972). The quotations and Fig. 3 are from this paper and are reproduced by permission.
20. H. D. Ratliff, personal communication.
21. This use of the term systems analysis is not to be confused with the meaning common in computer application activities.
22. As a recognition of this fact, much of what I call here systems analysis is sometimes called "policy science" or "policy analysis."
23. A classic military systems analysis is described briefly in nontechnical form in B. L. R. Smith, *The Rand Corporation: Case Study of a Nonprofit Advisory Corporation* (Harvard Univ. Press, Cambridge, 1966), chap. 6. For a short account of a major study for the New York City Fire Department, see E. J. Ignall *et al.*, *Interfaces* **5** (part 2 of No. 2), 48 (1975); for a fuller account see W. Walker, J. Chaiken, E. Ingall, Eds., *Fire Department Deployment Analysis: A Public Policy Case Study* (Elsevier North-Holland, New York, 1979). For a short account of a study of transport in the Sudan, see T. L. Saaty, *Interfaces* **8** (part 2 of No. 1), 37 (1977). For an account of a study for the Netherlands government, see B. F. Goeller *et al.*, *Protecting an Estuary from Floods—A Policy Analysis of the Oosterschelde*, R-2121/1-NETH (Rand Corporation, Santa Monica, California, 1977). For a general introduction to systems analysis, see E. S. Quade, *Analysis for Public Decisions* (American Elsevier, New York, 1975); a three-volume *Handbook of Systems Analysis* is in preparation at the International Institute for Applied Systems Analysis, Laxenburg, Austria. For a short introduction aimed at developing countries, see *Systems Analysis and Operations Research: A Tool for Policy and Program Planning for Developing Countries* (National Academy of Sciences, Washington, D.C., 1976). The literature sometimes contains accounts of techniques employed in systems analyses; for example, for a survey of models used in energy policy studies, see A. S. Manne, R. G. Richels, J. P. Weyant, *Oper. Res.* **27**, 1 (1979).
24. See, for example, I. R. Hoos, *Systems Analysis in Public Policy: A Critique* (Univ. of California Press, Berkeley, 1972); G. D. Brewer, *Politicians, Bureaucrats, and the Consultant* (Basic Books, New York, 1973); M. Greenberger, M. A. Crenson, B. L. Crissey, *Models in the Policy Process: Public Decision Making in the Computer Era* (Russell Sage Foundation, New York, 1976); G. Majone and E. S. Quade, *Pitfalls of Analysis* (Wiley, Chichester, England, 1980).
25. If we take professional society membership as an indicator of interest and at least some activity, the operations and systems research community consists of about 10,000 persons in the United States and Canada, and 25,000 to 35,000 worldwide. The work of this community is reported in some 35 central journals [see (*15*), vol. 1, pp. 17–18] and an internationally sponsored comprehensive abstracting journal, *International Abstracts in Operations Research* (North-Holland, Amsterdam), currently in its 20th year of publication.
26. For a 1972 view of the situation in the U.S. federal government, not much changed since, see H. J. Miser and W. E. Cushen, in *Management and Policy Science in American Government*, M. J. White *et al.*, Eds. (Lexington Books, Lexington, Mass., 1975), p. 23.
27. The Operations Research Society of America made an attempt in 1971 to address this issue; the result was widely debated but does not appear either to have had lasting influence or to have generated a more refined or general flow of thinking leading to generally accepted principles. For some of the items of the literature, see T. E. Caywood *et al.*, *Oper. Res.* **19**, 1123 (1971), and later correspondence in *ibid.* **20**, 205 (1972). The 1972 and 1973 issues of *Minerva* carried a series of relevant essays. See also *Manage. Sci.* **18**, B608 (1971).
28. See, for example: H. Boothroyd, *Articulate Intervention* (Taylor and Francis, London, 1978); C. W. Churchman, *The Systems Approach and its Enemies* (Basic Books, New York, 1979); and G. Majone, *Omega, the International Journal of Management Science* **8**, 151 (1980); *The Craft of Applied Systems Analysis* (International Institute for Applied Systems Analysis, Laxenburg, Austria, April 1980).

29. Some two dozen colleagues in operations research and systems analysis reviewed an early draft of this paper and provided me with comments and suggestions. Their contributions to this paper are hereby gratefully acknowledged.

Strip-mine terraces on Bolt Mountain, West Virginia, October 1970. [Photo, U.S. Department of Agriculture] →