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考调论词

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SECTION I

Foundations and Philosophy of Operations Research

I-1

THE HISTORY, NATURE, AND USE OF OPERATIONS RESEARCH

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1. THE BEGINNINGS

In 1935, as part of Great Britain's effort to prepare an adequate response to the growing menace of German air power, scientists began an urgent series of experiments aimed at locating aircraft by sending out radio waves from ground stations and then detecting the reflections from the aircraft, a scheme that soon came to be called radar. The work began at Orfordness, on Britain's east coast about 60 miles north of the mouth of the Thames, and continued at Bawdsey, about 10 miles further south, where later the research staff was based and newly designed equipment was installed.

The ensuing three years saw the technical capabilities of the detection equipment established and the practical methods of aircraft tracing and reporting worked out. But to achieve efficient interception the British fighter aircraft needed to be controlled and directed to the appropriate places. Separately—in the interests of secrecy—the "Biggin Hill experiment" proposed by Henry Tizard was mounted during the late months of 1936 and the early ones of 1937. Fighter aircraft from the airfield at Biggin Hill, just south of London, were used to simulate enemy aircraft tracked by ground direction-finding on their own voice radio transmissions. Other fighters were interceptors, also tracked by their own voice transmissions and directed over the same radios. B. G. Dickins led the analysis of the results.

Toward the end of 1937, the two systems—the Bawdsey work on detection and tracking of uncooperative attacking aircraft and the Biggin Hill work on the tracking and direction of cooperative defending fighters—began to be brought together. This work involved the closest possible cooperation between the scientists and the officers and men of the Royal Air Force, so that the best tactical operations of both equipment and men, air and ground crews, could be achieved. "Thus there grew up, between the summer of 1936 and that of 1937, the basic technique of operational control without which the Battle of Britain would not have been won and could hardly have been fought." [Clark, 1965] The work had moved from technical experimentation to the evolution of effective tactics, with the scientists and operating people working together indistinguishably.

As the new tactics were tested further in large-scale air exercises, the scientists turned their attention to measuring how effective they were. It was in connection with such work in 1938 that A. P. Rowe, then in charge of the scientific group at Bawdsey, referred to it as "operational research"—terminology he is thought to have originated.

Thus, it is fair to think of Bawdsey as the birthplace of operations research—still referred to in Britain as operational research—and the period 1935-1938 as the time of gestation of its basic concept.

By 1939, E. C. Williams, a leader of the work at Bawdsey, had moved to the headquarters of the RAF Fighter Command to join a new team under Harold Larnder that continued the work of tactical evaluation and improvement. Within the next two years this scientific work in cooperation with serving military officers had established its worth so convincingly that similar arrangements had been made at the RAF Bomber Command (under B. G. Dickins), the RAF Coastal Command (charged with the air war against submarines), and the British Army's Anti-Aircraft (A.A.) Command.

The major night air raids on Great Britain in the autumn of 1940 presented the A.A. Command with major technical and operational problems. To help with them, P. M. S. Blackett, a physicist who was later to win a Nobel Prize for his work on cosmic rays, joined the staff of the command, and had soon assembled an active and effective group that came to be known as "Blackett's circus." In March 1941 Blackett moved to the Coastal Command, where he established a new operational research section that made important contributions to the effectiveness of this command. In December 1941 Blackett was consulted about the possibility of forming an operational research section for the Admiralty, and wrote a brief memorandum on "Scientists at the Operational Level" that was to have considerable influence on both sides of the Atlantic [Blackett, 1962]. In January 1942 Blackett moved to the Admiralty to establish operations research work there.

Later the operational research section for A.A. Command became the nucleus of the British Army Operational Research Group, and sections had been established in every major British military command, both at home and overseas.

When the United States was brought into the war, both its Navy and Army Air Corps became aware of this successful use of scientists at operational commands. In 1942, Captain W. D. Baker, an antisubmarine-warfare officer with the Atlantic Fleet, requested the establishment of an Anti-Submarine Warfare Operations Research Group and drew from Blackett's 1941 memorandum in describing what he wanted it to do and how it should be manned. To lead ASWORG, later renamed the Operations Research Group and attached to the Headquarters of the Commander-in-Chief, U.S. Navy, Philip M. Morse, a physicist, was recruited from Massachusetts Institute of Technology to be project supervisor, and William Shockley, later to win a Nobel Prize for his work on the transistor, was brought from the Bell Telephone Laboratories to be director of research. During the same period, the U.S. Army Air Corps sent W. Barton Leach, a lawyer then on active duty, to England to study what had been done there; when he brought back a favorable report, he was asked to recruit scientists and to establish an "operations analysis section" at the Eighth Air Force, a bombing force that was then getting itself established in the United Kingdom. The first members of this section arrived on site in October 1942. By the end of the war the Navy's Operations Research Group had grown to over 70 scientists and the USAAF, under Leach's leadership, had established over two dozen operations analysis sections, both at home and at combat commands abroad.

The Royal Canadian Air Force also adopted the operational research concept in 1942, and organized three sections.

Quite independently, Ellis A. Johnson, capitalizing on an expertise in magnetism, developed similar concepts and applied them to the problems of mine warfare; his ideas applied to this offensive tactic played a significant role in the Pacific war [Johnson and Katcher, 1973; Page, et al., 1974].

The Axis powers did not make use of operations research during World War II.

The available historical records do not provide an accurate count of the number of scientists involved in operations research in World War II; however, even a conservative estimate suggests that the number in the British, American and Canadian services totaled well over 700. Their activities, far too various to summarize here, included not only the elements of technical support, evaluating tactical results, and tactical innovation mentioned earlier, but also applying such knowledge to tactical planning and strategic choices. Most important for the future, many of these men saw in these wartime scientific developments the germ of a new science of operating systems and applying the knowledge that it was capable of generating to many peacetime activities.

For sketches of the wartime work, see Air Ministry [1963] and Morse and

Kimball [1946], on which the brief account above is largely based, and Blackett [1962], Johnson and Katcher [1973], Page, et al. [1974], Trefethen [1954], and Waddington [1973].

Since World War II workers have identified many precursors of operations research as it came to be recognized during the war—for example, Lanchester's 1916 model of warfare [Morse and Kimball, 1946], Erlang's development of queuing theory and its applications in Copenhagen in the early years of the twentieth century (see Chapter III-2), and Levinson's work on the problems of retailing beginning in the 1920s [Levinson, 1954]. However, these precursors remained isolated until they joined the mainstream of activity and knowledge that flowed from the history that has just been sketched. Therefore, it is fair to identify the beginnings of operations research as a coherent professional field with a continuous history starting with the work of the World War II analysts.

2. THE SCIENCE OF OPERATIONS RESEARCH

It is clear that many of the early pioneers of operations research (OR) conceived of their work as being scientific; indeed, Blackett's early 1941 memorandum emphasized that the work was the "scientific analysis of operations," and stressed that conditions should be appropriate for such work: "The atmosphere required is that of a first-class pure scientific research institution, and the calibre of the personnel should match this."

In a second memorandum ("A Note on Certain Aspects of the Methodology of Operational Research"), originally written in 1941 but revised in May 1943 [Blackett, 1962], he goes on to say:

> One obvious characteristic of operational research, as at present practiced, is that it has, or should have a strictly practical character. Its object is to assist the finding of means to improve the efficiency of war operations in progress or planned for the future. To do this, past operations are studied to determine the facts; theories are elaborated to explain the facts; and finally the facts and theories are used to make predictions about future operations. . .
>
> Predictions about the future are of course always subject to much uncertainty, but experience has shown that many more useful quantitative predictions can be made than is often thought possible. This arises to a considerable extent from the relative stability over quite long periods of time of many factors involved in operations. This stability appears rather unexpected in view of the large number of chance events and individual personalities and abilities that are involved in even a small operation. But these differences in general average out for a large number of operations, and the aggregate results are often found to remain comparatively constant.

Morse and Kimball [1946] also observed 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."

Thus, the early workers saw clearly that the novelty of what they were doing arose from two sources: the phenomena of operating systems that were being subjected to scientific study, and the administrative arrangements that were evolved to enable the findings to be put to practical use promptly.

These early perceptions remain valid today.

2.1 Science and Its Method

The aim of science is to understand and provide explanations for what occurs in nature, that is, real-world phenomena. Our concept of nature includes both naturally occurring and man-made elements; the phenomena are any happenings or effects exhibited by these elements.

Science begins with carefully disciplined observations of selected phenomena. These facts then lead the scientist to construct theories that fit the facts and constitute an intellectual description and explanation of them. These theories can then be manipulated and extended entirely within the domain of the intellect; more importantly, they can be made to yield predictions of what will happen under various new conditions. These consequences of the theories can then be verified by new observations of the relevant phenomena; if the consequences of one's theory check with the observed facts, his belief in its correctness is strengthened, but, if consequences and facts disagree, then he must discard the theory or modify it.

Kemeny [1959] summarizes the process this way:

> As Einstein has repeatedly emphasized, science must start with facts and end with facts, no matter what theoretical structures it builds in between. First of all the scientist is an observer. Next he tries to describe in complete generality what he saw, and what he expects to see in the future. Next he makes predictions on the basis of his theories, which he checks against the facts again.
>
> The most characteristic feature of the method is its cyclic nature. It starts with facts, ends in facts, and the facts ending one cycle are the beginning of the next cycle. A scientist holds his theories tentatively, always prepared to abandon them if the facts do not bear out the predictions. If a series of observations, designed to verify certain predictions, force us to abandon our theory, then we look for a new or improved theory . . . Since we expect that science consists of an endless chain of progress, we may expect the cyclic process to continue indefinitely.

The process just described is *the method of science*, and *science* is the body of knowledge produced by applying this method to the phenomena of nature.

What unites all of science, then, is its method; what distinguishes one science from another is the domain of nature each has undertaken to understand and explain. Thus, for example, an astronomer looks at the motions of planets, stars, and other bodies in the universe; a geologist examines phenomena of the earth's crust; and so on.

One must be careful not to take this description of the structure of science as a behavioral description of the activities of scientists. While some scientific work does follow this outline, most does not: for example, theories are invented before phenomena are found that fit them (quite common in operations research these days), theories based on phenomena may go unverified for a long time, and so on. In sum, scientists may start anywhere in this outline, and move in any direction to achieve bits and pieces of knowledge. However, the final synthesis of confirmed knowledge is achieved in conformity with the structure of the method of science.

2.2 Operations Research as a Science

In the spirit of this philosophy of science, we may say that OR uses the method of science to understand and explain phenomena of *operating systems*, the natural context it has chosen to explore. Such systems frequently involve men and machines operating in a natural environment, where we understand the word machine to have a very general meaning, ranging all the way from the mechanical devices usually intended by the term to complicated social structures operating according to accepted rules.

Thus, the science of OR observes the phenomena of operating systems, devises theories (in recent years called *models* by many operations-research workers) to explain these phenomena, uses these theories to describe what takes place under altered conditions, and checks these predictions against new observations.

In sum, OR is a science because it employs the method of science to create its knowledge, and it is distinguished from other sciences by undertaking to account for the phenomena of operating systems, a context of nature largely neglected by other sciences.

In view of the steps in the method of science, one can expect any science to develop systematic literature in four categories: the results obtained from observing phenomena and specialized methods for making such observations, the construction of theories (or models), the tailoring of such theories to observations and the derivation of predictions from the results, and the verification of these predictions by comparing them with new observations.

Part II of this handbook describes deterministic theories that have been developed by operations research since World War II: linear programming, integer programming, graph theory, flows in networks, geometric programming, nonlinear programming, large-scale programming, and optimal-control theory. Part III covers eight stochastic theories, largely developed since the war: stochastic processes, the theory of queues, value theory, decision analysis, game theory and gaming, search theory, simulation, and dynamic programming.

Part IV describes important models that have been devised for thirteen processes common to many arenas of application: forecasting; accounting; finance and managerial economics; marketing and advertising; personnel management; investment economic analysis; management information systems; computer and information systems; project selection, planning, and control; inventory control; scheduling and sequencing; replacement, maintenance, and reliability; facilities location and layout; and production planning. There is also a section on cost-benefit analysis.

Part V describes how these theories—and others--have been tailored to describe the phenomena in nine of the arenas in which OR was well developed in 1974: military problems, government operations, urban systems, health services, education systems, transportation, public utilities, manufacturing industries, and the process industries.

The results of observations and methods of making them, as well as how they are used in formulating and verifying theories, are usually included in the literature supporting the summaries in Parts IV and V. Oddly, OR has not as yet developed a sufficiently specialized literature on these subjects to warrant separate discussion in this handbook. However, one can expect such a literature to emerge in the future.

In any case, it is fair to say that OR workers have, throughout the history of their subject, followed Blackett's advice (from his "Methodology" memorandum): ". . . operations research, like every science, must not copy in detail the technical methods of any other science, but must work out techniques of its own, suited to its own special material and problems. These techniques must not remain rigid but must change with the nature of the problems."

During World War II most of the OR work involved adaptations of methods and approaches from other sciences; in particular, most of the mathematical models were fairly direct constructions using the tools of analysis, probability, and statistics, frequently inspired by conceptual analogies from other sciences. A notable exception was the development in the U.S. Navy's Operations Research Group (ORG) of search theory (see Chapter III-6). Thus, the new theories summarized in Parts II, III, and IV are largely post-war developments. Lanchester's theory of warfare [Morse and Kimball, 1946] had existed since 1916, and, although explored mathematically during the war, was not applied directly to war-time operations; indeed, it did not achieve significant verification until 1954 [Engel, 1954].

Since World War II, however, the explorations of new phenomena of nature and the construction of theories to account for them has proceeded very rapidly, as Parts IV and V amply attest.

3. THE PRACTICE OF OPERATIONS RESEARCH

The science of OR was born in response to pressing operational problems. Thus, throughout the history of the subject, OR workers have done more than develop a science; they have also applied the knowledge gained to solving problems. During the second and third decades of its history, the community of OR workers has grown to be large and varied enough to enjoy some specialization—the growth of a community of theoreticians being particularly notable—but this close relation between research and practice remains a special feature of the subject: the term OR, indeed, comprehends both aspects. In sum, operations research includes both scientific research on the phenomena of operating systems and the associated engineering activities aimed at applying the results of the research.

However, this engineering aspect of OR involves more than just applying knowledge developed by the method of science; it also uses the arts of invention (finding arrangements that work in desired ways) and design (putting inventions together to perform desired tasks or solve important problems), not to mention the various arts of communication, interpretation, and implementation.

Military secrecy kept much of the detail of wartime studies from general publication for a long time; however, by now much of what was done then has been described publicly (see the references in the first section of this chapter). Similarly, industrial and institutional constraints continue to keep much of the work of OR practice from publication. However, the literature, although overbalanced in the theoretical direction by these constraints, does contain records of many fine examples of applied operations-research work—far too many for a compact listing in a handbook. On the other hand, what this means is that even a casual search of the literature will lead one to interesting and excellent examples—and, of course, the chapters in Part V refer to examples in their arenas. Readers interested in early examples now considered classics will find these three papers of interest: [Edie, 1954; Thornthwaite, 1953; O'Brien and Crane, 1959].

However, on the arts of invention and design related to the practice of OR, the literature is relatively sparse, and not yet well enough developed to call for a summary chapter in this handbook. The practice of these arts has achieved the most in the military environment [Quade and Boucher, 1968], but significant progress is now appearing in connection with civil-sector problems [Quade, 1975].

On issues of professional concern relating to practice, even the early writers showed concern and offered advice; for example, both Blackett [1962] and Morse and Kimball [1946], based on their wartime experiences, discuss how an analyst should go about his work, the conditions that should surround it, and the relations he should maintain with the users of his findings. In this area, four points deserve to be made here:

1. Chapter I-3 discusses issues relating to the conduct of OR studies.
2. A committee of the Operations Research Society of America (ORSA) has set forth some guidelines for the practice of operations research [Caywood, et al., 1971]. This effort met with considerable early criticism, and it is too early to tell whether or not the concepts, although well based on experience during the war and the first two post-war decades, will endure as permanent guides for practitioners in the changing conditions of the future.
3. The relations between OR groups and their client organizations have been fairly extensively studied; while there is no convenient comprehensive summary of this work, the reader will find [Radnor and Neal, 1973; Neal and Radnor, 1973] convenient entry points for a search of this literature.
4. The rather dry categorizations of this chapter look back at the history of OR, and, no doubt, describe much of its future. However, they almost completely ignore the fact that OR, when its scientific and engineering aspects are taken together, works in a setting provided by society—and, indeed, aims at understanding society's behavior in order to induce changes in it. In fact, OR activity becomes merely a part of the behavior of the system we call society. These perceptions lead naturally to important practical and philosophical issues, which are taken up in the next chapter of this handbook. Thus, the present chapter should be regarded as an introduction to the much more comprehensive social perceptions discussed in Chapter I-2.

4. THE GROWTH OF OPERATIONS RESEARCH, 1945-1975

There is not room in a single chapter of this handbook to set forth a comprehensive history of the growth of OR over the last three decades. In a sense, the other chapters provide much of the material for an intellectual history. Therefore, in very brief compass we shall outline here a few more administrative matters that offer a frame for the substance of OR discussed in the later chapters: some trends in evidence over the period, the creation and growth of professional societies, the founding and growth of journals, the increasing flow of books, and the growth of education.

4.1 Trends

Although most of the war-time OR workers returned to their prewar pursuits at the war's end, an important nucleus remained attached to the military services,