OPERATIONS RESEARCH AND MATHEMATICAL PROGRAMMING: FROM WAR TO ACADEMIA – A JOINT VENTURE

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Summary

The history of operations research told in this chapter concentrates on how operations research originated in the Second World War and how it moved from the battle fields to the universities in the USA together with mathematical programming, a subject that also emerged as a consequence of war work, moved into academia afterwards and early on became an important component of operations research.

1. Introduction

Operations research (OR) originated during the Second World War as a means through which scientists and mathematicians contributed to the war effort. After the war its proponents advocated operations research for peacetime purposes for use in government and industry and created the academic discipline of OR. Its origins and rapid growth have made OR difficult to define precisely. According to one dictionary operations research is "Mathematical or scientific analysis of the systematic efficiency and performance of manpower, machinery, equipment, and policies used in a governmental, military or commercial operation" (Gass and Assad, 2005, p. ix). One of the first official definitions of operations research was given by Philip M. Morse and George E. Kimball in what is considered to be the first textbook of operations research. They wrote:

> Operations research is a scientific method of providing executive departments with a quantitative basis for decisions regarding the operations under their control. (Morse and Kimball, 1951, p. 1)

During the process of establishing operations research as an academic discipline the definition of OR was an ongoing issue that was debated in the first OR journals and in proceedings from the international conferences. Morse tried unsuccessfully to stop the debate at an early stage by simply stating that:

> We should no longer have trouble explaining the scope and methods of operations research to the layman. We already can say: operations research is the activity carried on by members of the Operational Research Society; its methods are those reported in our journal. (Morse, 1953, p. 159).

But, because operations research covers a broad variety of activities and methods, OR people still have problems drawing the disciplinary boundaries defining OR, and the problem of what operations research is still haunts the profession. In the book *An Annotated Timeline of Operations Research* from 2005 two of its practitioners Saul I. Gauss and Arjang A. Assad discussed the question of how to "negotiate the boundaries between OR, economics, industrial engineering, applied mathematics, statistics, or computer science, not to mention such functional areas as operations management or marketing?" and they conclude:

> We recognize that the answer to this question [What is OR?] and the drawing of the boundaries of OR varies depending on the background and interests of the respondent.

This is of course also true for the picture of operations research that will be drawn in this chapter. As indicated in the title the focus will be on the history of how OR originated in the Second World War and how it moved from the battle fields to the universities in the USA together with mathematical programming, a subject that also emerged as a consequence of war work, moved into academia afterwards and quickly became an important component of operations research.

2. Precursor of OR: Taylorism

Taylorism is often mentioned as a precursor of OR. It is named after the American engineer and management consultant Frederick Winslow Taylor (1856-1915). To overcome the ineffectiveness in industry he proposed systematic management based on scientific principles. His book *The Principle of Scientific Management* was published in 1911. In the first chapter Taylor emphasized that "The principal object of management should be to secure the maximum prosperity for the employer, coupled with the maximum prosperity for each employé." Scientific studies of work tasks involving observation, experimentation, and mathematization to optimize a day's work were an essential part of Taylor's scientific management. One of the examples often quoted is his calculation of the optimal load workers should carry on their shovels. The study took place at Bethlehem Steel Company and resulted in a reorganization of the work of the shovelers. It was found that a shoveler's optimum workload for a day was reached if the load on the shovel was approximately 21 pounds. Instead of each shoveler owning his own shovel a variety of different kinds of shovels were purchased to make "it possible to issue to each workman a shovel which would hold a load of 21 pounds of whatever class of material they were to handle: a small shovel for ore, say, or a large one for ashes." (Taylor, 1911, p. 66). The study also changed the organization of the daily work from having the 600 shovelers and laborers organized in big groups under a few foremen to a detailed system directing each man's work.

3. The Beginning of OR in Britain: The Use of Radar in Anti-aircraft Warfare

The field that developed into the discipline we know today as operations research originated in the British military in the second half of the 1930s as a response to the mobilization of the German air force. The British government established the Committee for the Scientific Survey of Air Defense in 1934 charged with investigating the scientific possibilities for developing an effective anti-aircraft defense. Sir Henry Thomas Tizard (1885-1959) who was a chemist became the chairman of the committee, which was also known as Tizard's Committee.

The possibility of using radio waves to detect enemy air crafts proposed by the physicist Robert Watson-Watt (1892-1973) was presented to Tizard's Committee in February 1935. A year later the British Air Ministry established the Bawdsey Research Station in Bawdsey Manor in Suffolk, and it became the main center for radar research.

In 1938 the British held a massive air defense exercise that showed that on the one hand from a technical point of view the radar system could be used to detect air craft, but on the other hand there were problems related to the actual use of radar. The superintendent Albert Percival Rowe (1898-1976) at Bawdsey Manor then organized teams of scientists and engineers to do research into the operational aspects of the use of radar. These groups are generally acknowledged as the first OR sections. At the outbreak of the war in 1939 these teams were attached to Royal Air Force Fighter Command as the Stanmore Research Section that was renamed the Operational Research Section in June 1941.

The success of these operational researchers led to the establishment of OR teams in other parts of the Royal Air Force as well as in the navy and the army. In 1940 the physicist Patrick Maynard Stuart Blackett (1897-1974) formed the operations research team known as "Blackett's Circus" to investigate the use of radar in anti-aircraft gunnery. Blackett's group consisted of three physiologists, two mathematicians, two mathematical physicists, one astrophysicist, one Army officer, one surveyor, and one physicist, thus exhibiting the multi-disciplinary feature of operations research. Blackett is often credited as the most important person for the development of operations research in Britain, and besides Blackett's Circus he also formed OR groups in the Coastal Command.

In the beginning the OR groups primarily worked with problems related to the use of radar in anti-aircraft and anti-submarine warfare but their work area was gradually expanded to include other problems including strategy and logistics.

During the war the tasks of the OR groups were to find optimal ways to use existing military forces, weapons, and other equipment. They were characteristically multi-disciplinary in composition, being made up of various scientists such as biologists, physicists, chemists, engineers, and mathematicians, and they worked close to the military operations gathering data and analyzing what went on. The close connection between OR teams and the military operations is often emphasised as one of the reasons behind the success of operations research. (See (Fortun and Schweber, 1993), (Kirby and Capey, 1997)).

4. OR's Move to the US Military: The Mobilization of Civilian Scientists

In the USA civilian scientists were mobilized for the war effort in great numbers, a process that was spearheaded by electrical engineer Vannevar Bush (1890-1974). His vision was to develop an organizational structure that would make scientific research in warfare, defense, and development of new weapons more effective. In 1940 the National Defense Research Committee (NDRC) was established under President Roosevelt with Bush as chairman and in 1941 Bush became the leader of the Office of Scientific Research and Development (OSRD) which was founded as an umbrella organization with NDRC as one of its sections.

Operations research was imported from Great Britain and incorporated into OSRD in the fall of 1943 as Office of Field Service. Bush and OSRD have been named the key players in the promotion of operations research in the USA during the Second World War but newer research has shown that operation research was implemented into OSRD not because of but in spite of Bush. According to the historian Eric P. Rau operations research did not fit into Bush's organization due to "incompatible strategies of organizing research and development for the war effort" (Rau, 2000, p. 57). Civilian scientists were organized through OSRD by contracts with the military. The scientists were only involved with research and development and they were under civilian authority independent of the military. Bush constructed this contract-policy of OSRD to ensure that the scientists would not have any further commitments to the military once the work specified in the contracts was done. Bush organized the scientific mobilization in this way deliberately in order to protect civilian research institutions from government influence in the future. OSRD proved itself to be a very effective and successful organization through which American scientists and mathematicians came to play decisive roles in the Second World War but when it came to operations research the result of the contract-based organization was a division between the scientists involved with the development of new weapons and defense systems on the one side and the military personnel who were to use these developments on the other side. This structure was indeed incompatible with operations research that was developed in Great Britain exactly to function as a mediating link between the producers of new technologies and the users of these new tools.

In May 1942 Bush wrote to Brigadier General R. G. Moses and Rear Admiral W. A. Lee that "NDRC is concerned with the development of equipment for military use, whereas these groups [OR groups] are concerned with the analysis of its performance, and the two points of view do not, I believe, often mix to advantage. … [The] type of man to be used in such work is very different from the type needed for experimental development" (Rau, 2000, p. 69). This opinion held by Bush stood in strong contrast to the experiences of the British OR groups, and different sections of the USA military formed OR groups during 1942. They sent many requests for personnel from OSRD to staff these groups and in 1943 Bush finally gave in and operations research was officially implemented in OSRD as Office of Fields Service (OFS).

5. ASWORG: Philip Morse's OR Group

The Antisubmarine Warfare Operations Research Group (ASWORG) became one of the better known OR groups in the US during the Second World War. It was established within the Anti Submarine Warfare Unit in the US Navy in 1942 with Captain Wilder D. Baker as chief. With support from the physicist John Torrence Tate (1889-1950) who was chief of NDRC's Division 6 (Sub-Surface Warfare), Baker asked the physicist Philip McCord Morse (1903-1985) from Massachusetts Institute of Technology (MIT) if he would "organize a scientific task force to help his [Baker's] unit analyze the U.S. antisubmarine effort" (Morse, 1986, p. 12).

Morse's group was established in April 1942 and staffed with scientists, mostly mathematicians and physicists. One of the first studies the group undertook was to develop a search theory for aircrafts patrolling oceans to locate enemy submarines. One of the first major obstacles the group encountered was the lack of relevant data, especially quantified data. To overcome this, scientists from the group received permission to go to the anti-submarine bases, join some of the flights, and collect the necessary data themselves. They were then able to calculate explicit search plans that the Anti Submarine Warfare implemented, resulting in a considerable increase in the number of submarine sightings per week. Another change of practice that the group recommended as a result of their studies of operations was the setting of the depth charges the aircrafts dropped when they attacked the submarines. The usually depth setting for the charges was seventy-five feet, which was the setting used when the attack was performed from a destroyer. This setting worked fine with destroyers that usually attacked submerged submarines but it was not very effective when the charges were dropped from aircrafts. The group recommended that the depth-setting was changed to thirty feet. The number of submarines sunk improved significantly.

During the war the group was expanded into the Operations Research Group, and after the war it was renamed the Navy's Operations Evaluation Group.

6. The Applied Mathematics Panel: OR Training Courses During Word War II

The Applied Mathematics Panel (AMP) was established under NDRC towards the end of 1942 to organize the mathematicians for the war effort. Warren Weaver (1894-1978), a civil engineer and mathematician, was head of the AMP and he was convinced that the scientific development that went on under contracts with OSRD would benefit from scientists' involvement with and understanding of what went on in the field. In February 1943 – that is before the establishment of Office of Field Service – Weaver expressed his frustration over the OR-situation in a letter to Bush in which he pointed out that the NDRC divisions "are solely in need of better contact with the Operational Research Groups. At the present time the former simply are not getting the data from the latter." (Rau, 2000, p. 73-74). The Applied Mathematics Panel, along with other NDRC divisions, went ahead and developed its own training programs in operations research.

This "re-education" of mathematicians into operations researchers has been evaluated as one of the successes of the Applied Mathematics Panel's work during the war.

During the war mathematics was part of operations research right from the beginning. Half of the people in Morse's original group were mathematicians and the mathematicians that were trained in operations research in the Applied Mathematics Panel's courses were in high demand by the military. An often-cited example of this is the request from the Air Force for more AMP-educated mathematicians to study aerial flexible gunnery problems. Mathematical theories and mathematical modeling were considered essential techniques and methods of operations research, especially game theory and linear (or more generally) mathematical programming were often, and still are, associated with operations research, the latter to such an extent that it sometimes was used synonymously with operations research.

7. Game theory: The Significance of John von Neumann

The book *Theory of Games and Economic Behavior* written by the mathematician John von Neumann (1903-1957) and the economist Oskar Morgenstern (1902-1976) was published in 1944. It was the first coherent treatment of game theory and its application in economics.

The French mathematician Émile Borel was the first who tried to treat games of strategy from a more systematic point of view. He wrote a series of short papers and notes on this during the 1920s, but the first substantial paper on games of strategy with an interesting mathematical result, the minimax theorem, was published in 1928 by John von Neumann. (See (Kjeldsen, 2001)).

Von Neumann considered a game for two players with a finite number of pure strategies, and a pay-off function by which the gains and loses can be calculated. He assumed the game to be a zero-sum game which means that one player's gains equal the other player's loses. The minimax theorem states that such a game has a value V, and that there exists a set of mixed strategies, called the optimal strategies, one for each player, that ensures player I an average payoff of V, no matter what strategy player II chooses, and ensures player II an average payoff of $-V$, regardless of which strategy player I chooses. These strategies form an equilibrium of the game. For mixed strategies, the function that describes the expected value of the game is a bilinear form and an equilibrium point for the game, or a minimax solution, is constituted by a saddle point for this bilinear form. The famous result of von Neumann, the minimax theorem, states that for two-person zero-sum games such a saddle point exists.

Game theory was added to the OR toolbox of mathematical techniques probably as a result of von Neumann's influence, because he held many consulting jobs for the military both during and after the war.

8. The Origin of Linear Programming: Logistic Planning in the Army Air Force

Linear programming came out of work done primarily by the mathematician George Bernard Dantzig (1914-2005) in the US Air Force during and after the war. Dantzig was employed by the Army Air Force's Combat Analysis Branch of Statistical Control in

1941 to work on what they called "programming planning methods". An Air Force program was a schedule for activities, a huge logistic plan that was based on data such as number of flown sorties, dropped bombs etc. which were then used in organizing forces and equipment, scheduling training, providing logistic support for activities etc. One of the problems was that it took about seven months to calculate such a program. After the war Dantzig worked as mathematical advisor to the comptroller of the Air Force on how to speed this up by mechanizing the process of programming planning.

The first electronic computers were constructed during the war. By the end of 1946 it became clear that such computers could be used in the calculating of air force programs. This changed the character of the work, as Walter Jacobs explained in his progress report on the Air Force's use of scientific procedures in programming and planning:

> By 1947, a small group had become convinced that mathematical techniques, backed up by large-scale electronic computers, were needed in tackling the programming problem. Since no suitable computer existed, the Air Force undertook to support the development of the necessary equipment. In furtherance of these activities, Project SCOOP was established in October 1948; the initials stood for Scientific Computing of Optimum Programs. (Jacobs, 1957, p. 214).

Dantzig worked on the project from 1946 to 1952 developing a mathematical linear model for the Air Force programming problem based on Wassily Leontief's economical Inter-industry Input-Output Model. With the advent of the computer the possibility of comparing consistent programs in order to choose for example the cheapest one became an option and an objective was implemented in the model, as formulated by Dantzig and Wood in December 1948:

> We seek to determine that program which will, in some sense, most nearly accomplish objectives without exceeding stated resource limitations. (Dantzig and Wood, 1949, p. 195).

The mathematical model Dantzig ended up with was the following: the optimization of a linear form subject to linear equations and inequalities. It was named linear programming and is identical with the formulation of a linear programming problem given in most textbooks today. Dantzig also developed the simplex algorithm for solving linear programming problems while he worked for the Air Force.

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Biographical Sketch

Tinne Hoff Kjeldsen, - Associate Professor of mathematics at IMFUFA, Department of Science, Systems, and Models, Roskilde University, Denmark. Her work includes contextualized historical analyses of the emergence and development of nonlinear programming in the USA, and the significance of World War II for this development. Her current research concerns the history of the theory of convexity, and the history of mathematical modeling in biology. Her main interests include history of twentieth century mathematics, history and philosophy of mathematical modeling, historiography, and didactics of mathematics especially regarding modeling competencies and the use of history in mathematics and science education. Her research results are published in major journals of history and philosophy of mathematics and science.