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Organon 4, 253-265

1967

Artykuł umieszczony jest w kolekcji cyfrowej Bazhum, gromadzącej zawartość polskich czasopism humanistycznych i społecznych tworzonej przez Muzeum Historii Polski w ramach prac podejmowanych na rzecz zapewnienia otwartego, powszechnego i trwałego dostępu do polskiego dorobku naukowego i kulturalnego.

Artykuł został zdigitalizowany i opracowany do udostępnienia w internecie ze środków specjalnych MNiSW dzięki Wydziałowi Historycznemu Uniwersytetu Warszawskiego.

Tekst jest udostępniony do wykorzystania w ramach dozwolonego użytku.



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THE USE OF MATHEMATICAL METHODS AND COMPUTERS
FOR ANALYSING TENDENCIES OF
DEVELOPMENT OF SCIENCE AND ENGINEERING

NEEDS AND TASKS

All sciences, developed under the influence of vital inquiries and social practice are constantly taking care of improving their methods, as well as putting and solving problems which become more and more complicated. "The scientific study of things has two principal or final aims: foreseeing and profit," as Mendeleyev said [1].

This observation refers also to the history of science and technology. Scientists working in the field strive to generalize the experiences of progress and to foresee its future routes. These aims make the problem of further development of methods of investigation used in this field actual in a new way.

The history of science knows, that all branches of science pass in their development through such essentially different stages as:

1) the descriptive one, in which the facts and observations are collected and primarily systematized;

2) the logico-analytical one, in which the phenomena are being analysed quantitatively;

3) and the last stage, synthesizing qualitative and quantitative methods.

Referring to this tendency in the development of science K. Marx said: "Science only then attains perfection, when it succeeds in using mathematics." [2]

Various quantitative methods and modern technical means of data processing are typical for today's history of science. Of course, the use of mathematics and computers in the investigator's work does not diminish the significance of qualitative methods of analysis mastered

before. To the contrary, it imposes high demands on the level of really scientific methodology and gives to the scientist new important facts, grounds and possibilities for deeper understanding of the phenomena.

Problems of the history of scientific and technological progress, which are being studied with the help of new methods, deal closely with the fields of interest of many branches of science and engineering, those of information services and of institutions controlling the development of science and technology.

Actualization of tasks is a natural result of the development of the history of science. Scientific and technical progress as a whole embodies the past, the present and the future. It inherits past experiences and traditions, reflects the modern views, possibilities and needs and finally it bears the corns of methods and ideas of the future.

The increasing general rate of scientific progress and its growing interdependence with other aspects of life stipulate obvious changes within the very idea of the "History of Science." What took whole centuries before is nowadays performed within some decades. The historical period of the past 65 years of our century comprise more than $\frac{2}{3}$ of all scientific and technical achievements and over 90% of all scientific information worked out by mankind.

In our opinion, history of science should be looked at as scientific, trustworthy information concerning the scientific and technological experience of the past, generalized at the contemporary level of knowledge.

Such an approach is usually connected with considerable methodical and technical difficulties. At the same time there is too much and too little information. This is even more essential for historians, than for scientists in any other field—since the solving of historical problems demands facing wide fields of information, covering a long time-period as a rule.

The mass of scientific and technical information accumulated by mankind is doubling each 10—15 years. This leads to growing losses of useful data. The lot of duplicated "discoveries" and repeated "inventions" is growing. It is known, that $\frac{2}{3}$ and often more of all patent declarations repeat the inventions made before.

One may assert that we know more and more about the mysteries of nature and the possibilities of technique and, at the same time, a constantly diminishing part of what is already no mystery for history becomes available to us.

Without denying the necessity of reaching the aims of historical chronicles of progress, life suggests new problems, especially inherent to two directions being formed now:

- a) "science of science"
- b) "concrete historico-technological investigations."

The first direction is being formed on the basis of a new approach to the study of the history of science and the second one—on the basis of mastering new methods of research on the history of technology.

It is possible to try to formulate the principal tasks of above directions [3]. They are: to generalize the experiences of development; to acquire such knowledge of the world of scientific and technological progress which would enable to assist the optimisation of the process of development with the help of social and organizational influence.

The form of output of "final results" of investigation in this field should of course be renewed. As the new methods of investigation are being mastered, concrete proposals based on the scientific analysis of history should be presented to the agencies controlling scientific and technological progress. The practical participation in creating actual information systems can help to use more fully the experience of the past.

Such aims make the task of mastering mathematical methods and using modern computing techniques in our historical investigations especially important.

The history of science and technology sensed since long the need for new methods. In recent years, when this need became especially acute, the possibilities to satisfy it have been enlarged due to general scientific progress. We have to be prepared for the fact that general rapid progress of information and computing techniques, along with the achievements in mathematics and cybernetics will open in the close future new wide possibilities of effective processing of huge amounts of historico-technological and historico-scientific information.

Deep study of the logic of scientific and technological creation, preparing the classification of science and technique, the study of moving reasons and contradictions in development, scientific analysis of the role of social and economic factors of progress and regress—all those are necessary and important conditions in mastering new methods and technical means of research on historical problems.

CONTEMPORARY EXPERIENCE

First of all is possible to point out four types of problems which differ in levels and methods of solution:¹

- 1) information retrieval;
- 2) statistical and computational problems;

¹ This basic common character of processing information exceeds the limits of the history of science alone. We can point out problems at various levels in all sciences mastering computer methods of data processings. It is appropriate to mention here the analogy between the "science of science" and structural-mathematical linguistics, as well as between concrete historico-technical analysis and concrete sociological investigations.

- 3) logical (comparative) information analysis;
- 4) study of phenomena and modelling of processes.

The difference between the problems consists in depth and logical complexity of processing information, while on each level the problems are extremely varied in actual details [4, 5].

1) *The collection of data, documents, bibliography and other similar problems determined as "information retrieval"*. These are usually labour-consuming tasks. Viniti, patent service and cybernetics have valuable experience in this field for the historian of science [6, 7]. The historian M. Braichevsky in co-operation with the Institute of Cybernetics (Kiev—E. Skorokhodko) carried out a successful experiment in compiling bibliographical surveys on archeology in the Ukraine using the computer "Ural—L." [8]

The Department of History of Technology and Natural Sciences of the Academy of Sciences of the UkSSR (G. Dobrov, L. Smirnov [9, 10]² together with the cybernetists from Donetsk (A. Piatkin, M. Fedorenko) solved on the computer "Ural—I" a number of problems concerning retrospective search for materials in the field of history of technology [11, 12]. At the Institute of History of the Estonian Academy of Sciences (U. Kaakhk, H. Palli) punch-cards with the edge perforation are widely used for similar aims [13]. Historians of technology S. Shukhardin, V. Klimeniuk have worked out a universal punch-card index for registering events and facts concerning world history of scientific and technical progress [14].

The search for historical material with the help of perforation technique (the system of "Aritma") has been successfully mastered by the Institutes of History of the European Socialist countries such as the Czechoslovak Academy of Sciences [12]. The experience of using edge and machine punch-cards in various investigations on the history of science and technology has been forwarded also in the Laboratory of Machine Methods of Processing Historico-Technical Information of our Department [16].

2) *The analysis of quantitative statistical regularities of different processes over time*. For the majority of sciences which have since long taken the path of mathematisation this is a well mastered method. Active penetration of mathematics into branches of knowledge begins, as a rule with formulating and solving statistical calculating problems of different kind. The mathematisation of classical humanities and in particular of the historical sciences has begun in the same way.³ V. Us-tinov, a historian and specialist of computer techniques from Novo-

² The authors are working at the Laboratory of Processing Historical Information.

³ See, for example, the reports of the All-Union conference on *Cybernetics and methods of historical investigations*, Moscow University 1965, 17.

sibirsk, became a pioneer in solving such problems for different human sciences, basing on sources of mass information [18, 19] Having started with the brilliant work of decoding ancient Maya inscriptions, having solved a series of problems put forth by the historians of the working class and peasantry of the USSR (Z. Karpenko, J. Kovalchenko) [20, 21], V. Ustinov together with A. Deyev recently pay much attention to the task of preparing a library of standard programmes for problems of a similar kind, especially those serving for concrete sociological investigations [10]. Such experience of using the computer has also been accumulated in other historical investigations [9, 22].

A series of various statistical problems concerning the historical experience of science organization has been solved in the USA by D. Price [23, 24, 25] and by his assistants (L. Badash, D. Britton and others). An interesting historical and scientific analysis of the comparative accuracy of astronomical data given by Ptolemy, Copernicus and contemporary scholars was carried out by O. Gingerich at Harvard University [26]. Czechoslovak scholars I. Folta and L. Novy [27] have analysed on detailed statistical material historical tendencies in the development of mathematics for more than 200 years. The Laboratory of Computer Methods of Processing Historico-Scientific Information in Kiev has solved some of the statistical problems of analyzing the historical experience in the field of inventions and tendencies of scientific development (G. Dobrov, L. Smirnov, V. Klimeniuk) [9, 28].

3) *Logical analysis of scientific information.* These problems include the comparison of information contents the establishment of proximity, degree of similarity and the level of novelty, the definition of succession and trends in the historical development of events and phenomena. In archeology and historiography these are problems of identification and dating of material sources.

In the field of historico-technical analysis we tried to establish, together with E. Skorokhodko and E. Levin, and with the aid of a computer, the degree of similarity between different technical and scientific solutions, established at different times [9, 10].

In the Lebanon H. Haddad and E. Kennedy solved the problem of identification of ancient names in the field of history of geography [29].

Attempts at working out prognosing judgements concerning the features of technology during the next 10—15 years on the base of analysing trends in the inventing experience, within definite branches of technique (Moscow—I. Ivanov, B. Tardov and others) [9, 30], are of particular interest and high actuality.

4) *The modelling of processes and phenomena of historical development.* This is an especially complicated and important class of problems

which is closely connected with working out generalized scientific ideas and creating a logically capacious and mighty mathematical body of science.

Interesting attempts are known to describe directly the historical phenomena with the help of mathematical equations [31, 32], but those attempts have not yet been developed and realized.

The generalizing methodological works [33, 38] have special significance for successful use of cybernetical tools in history.

The Kiev cybernetists under the leadership of V. Glushkov have performed perspective attempts of modelling the historical processes of evolutionary development. (A. Letichevsky, A. Dorodnitsina) [39]; they are elaborating the machine language of scientific information (Z. Skorokhodko, L. Pshenichnaya, T. Gryasnukhina) [40].

In the Laboratory of Computer Methods of Processing Historico-Scientific Information, a pattern of the structure of the historical flow of information on technical ideas and typical models of the mechanisms of science interaction (i.e. the process of differentiation and integration of science) have been worked out [41].

Some interesting perspectives for concrete study and modelling the structure of logical connections in the process of historical science development opens the *citate index* method, which was successfully used in historico-scientific investigations by J. Bernal [43] and G. Garfield [43, 44]. It is seen from this short review that there is a variety of modern technical means, allowing to solve effectively different kinds of historical and technical problems. One should clearly distinguish three levels of technical means which increase according to their complexity and possibilities:

A) punch-cards with edge perforation and the so-called "small mechanization" of information work;

B) computer punch-cards, sorters and tabulators to work with them;

C) computers.

To be better oriented on such means, one should in our opinion be guided by the following complex of criteria:

a) the size of the accumulated store of information;

b) the rate of historical increase of the information;

c) logical complexity of the problems being solved;

d) frequency of the repeated use of historical information available;

e) difficulties in preparing the data.

Proceeding from the available experience it is possible to give a generalized summary of possibilities of processing information at various technical levels, as applied to the main types of problems being solved (Table).

The survey projects presented below express a wide and increasing range of interest in the use of mathematical and computing techniques for means of historical investigation. On the other hand it should be definitely stressed, that investigations in these perspective directions are still in the stage making. The fact, that during those last years stable scientific bodies have been formed in some countries, and that those bodies are engaged in investigation concerning the "science of science" as well as concrete historico-technical analysis, has to play an important part.

Level of computer techniques	Types of problems			
	Retrospective retrieval	Statistical computing problems	Logical analysis of information	Modelling of historical processes
Punch cards with edge perforation and means of "small mechanization"	Yes	Partly	No	No
Computer punch-cards, sorters, tabulators	Yes	Yes	Partly	No
Computers	Yes	Yes	Yes	Yes

Thus, the Institute of the History of Science, the leading study of which concerns "science about scientific activity," has been functioning at Yale University, USA (chief, prof. D. Price).

A Department of "science of science" (chief, prof. A. Tuszko) was organised at the Institute of the History of Science and Technology of the Polish Academy of Sciences. The leading scientific problem there is the generalizing of the experience of perspective science planning and the analysis of the effectiveness of scientific activity.

The Institute of Theory of Science Organisation and Planning of the Czechoslovakian Academy of Science (chief, prof. B. Starnovsky) has been generalizing the experience of science organization.

A specially formed research working group at the Presidium of the German Academy of Science in Berlin, G. D. R. (H. Müller, F. Barnetski) has been developing methods of estimating and analysing the results of scientific activity and generalizing the experience of science prognostics.

General methodological problems of the theory of science are being studied at the Institute of the History of Science and Technology of the Academy of Science of the U.S.S.R. (B. Kedrov, S. Mikulinsky, N. Rodnyi).

For the Section of Machine Methods of Processing the Historico-Scientific Information of the Department of the History of Technology and Science of the Academy of the Ukraine the leading problems are:

1) Profound historical and technical analysis of technological experience and of concrete regularities of creative invention in important branches of technique. We think, that the results of such investigation could be inculcated in practical work of existing information services.

2) Scientific analysis of historically shaped levels of science and historical experience of organization of scientific activity. The results of such work would be useful for organs controlling scientific development.

3) Preparing basic works on the history of scientific and technical progress using traditional materials from different sciences and also results, achieved with the help of new methods of investigation. Concrete attempts at prognosticating historical ways of scientific and technical progress should be undertaken in such works.

PERSPECTIVE PROBLEMS

We hope, that once the new directions of investigation have been outlined, the improving of their methods will be useful for turning the interests of the historians of science to the needs of life and practice. It is possible, that the attempt to outline the present and future problems of the two new directions of investigation in contemporary history of science and technology will be of use for this work.

Perspective problems of concrete historico-technical analysis

1. Introducing the historico-technical information in such a form, which would enable its further processing by using machine languages and methods of coding the historical information. The results of mathematical linguistics and scientific documentation are used here.

2. Information concerning inventive and designing experience in concrete branches of technology which has been collected and analysed by historians, should be used while solving problems of information. (For example — selection of material according to subject matters; "signal" information of patent connections etc.) Such material should also serve for solving various statistical tasks. (For example—analysis of statistical distribution, frequency characteristics, correlation, etc.)

3. Working out a set of "standard" programmes for concrete historico-technical analysis of inventive and designing experience. Fulfilling the algorithm of identification of the contents of the "found anew" or "supposed anew" decisions with the technological ideas accumulated before. Realizing the programmes of analysis of the historical experience, which takes into consideration the relative significance of various technical ideas and their logical interconnections.

4. Practical participation of the historians in creating information-reference systems, which aim at: a) operative information about possible (approved) versions of solving technical problems; b) objective evaluation of changing tendencies in concrete fields of engineering; c) working out a system scientifically based upon prognosing suggestions and technical conditions.

5. Profound study of concrete historical regularities and trends in technical creative work. (For example—modelling some aspects of the historical process of technical development; attempt at exposing the algorithm of inventive activity in concrete branches of engineering.)

6. Combining qualitative analysis with the defining of concrete quantitative characteristics of the historical process; it is possible to prepare fundamental works dealing with the history of definite technical means with fields of technology and with technical development as a whole.

Problems concerning the general science of science

1. The making of a formal and mathematical body of the "science of science". Side by side with wider and more delicate use of statistical methods one has to master here other mathematical methods.

The systems approach to the study of science and its structural analysis will improve on this basis. Putting into practice the ideas and possibilities of modelling the processes of scientific development is also bound up with improving the mathematical body.

It is obvious, that the most important preconditions for successful use of the mighty means of contemporary mathematics are: the making of a formalized language, the formation of a definite system of notions and, what is especially important, the working out of concrete indexes for various characteristics of scientific development. It is possible to presume, that investigations in this field will in the course of time, form a trend which will deserve the name of "scientiometrics."

For scientists generalizing the many years of experience of scientific development this trend should create a mathematical body of historical analysis which would meet their specific demands. The use of it, will in turn allow the science of science to make a contribution to the theory of scientific documentation and to the practice of scientific information services.

2. The study of the historical experience of labour organization in the field of science.

This problem will require the use of some of the methods of concrete sociological investigations, and also of some results and methods worked out by "engineering psychology." On this basis historians will be able to study thoroughly such traditionally interesting problems as "scientific schools," the history of communities of creative workers and the analysis of creative activity of many outstanding men of science. One should expect the results in this field to be a concrete contribution to that future scientific subject, which is sometimes called: "scientific labour organization in science."

3. The analysis of historical changes in the development of science organisation and the search for optimal structures of scientific staff and of scientific institutions.

All this is a valuable source of practically important conclusions and observations. A similar kind of analysis can lend new impact to the study of the history of formation and development of large scientific organizations, such as the Academy of Sciences of the U.S.S.R.

4. The problem of historical changes in various aspects of effectiveness of scientific activity.

We face a number of problems here, starting with the level of scientific activity and individual results, and ending with economic effectiveness of science. Using such data one may expect the analysis and the estimations of the history of science to be integral and convincing. One may also expect results, valuable for the "economics of scientific activity" which are now being formed within the general framework of economic sciences. The experience and results obtained in this field may be of essential value for solving problems of financial policy towards science, based on estimating the results of the activity of scientific institutions and the expediency of scientific trends.

5. The study of the experience of functioning of scientific systems and their interaction with other sciences, with engineering and with industry.

It is obvious in the general historical plan, that no "chronicle" of science can have a really scientific character without including original experience of such interaction. It should be expected that the results of solving the above problems will be widely used for study on the now urgently needed research topic, concerning the "scientific basis of planning and controlling scientific activity." And even before this subject comes to life, the results obtained by the investigators of the history of scientific and technological progress may be of use for solving problems of the tactics of science planning.

6. Generalisation of the experience in prognosticating the ways of science.

Working on this problem means the exposing of one more precious facet of a single, in its essence, historical experience of science. It is possible for future investigations in this field to develop into a new scientific trend, the "theory of scientific prognosticating." Such historic experience in prognosticating may be of great use for solving practical problems of preparing the strategy of science and of its perspective planning.

7. Studying the functioning of science as a whole in its interaction with society.

Contemporary science possesses a basic amount of investigations in the field. They enter under the heading: "Sociology of science." New aspects of this problem, full of present interest, are linked up with the processes of contemporary scientific revolution. The results of research having been enriched and particularized by way of new methods of specific sociological approach are called to become a contribution in the course of preparing scientific grounds for government policy towards science.

8. Working out the generalizing concepts of science of science, as the science about scientific activity as a whole.

This work is aimed at giving a single methodological approach to the analysis, the estimations and the solving of many different "science of science" problems. It may be supposed, that such conceptions will arise while using the ideas and experience of natural sciences (e. g. information theory), of philosophy (e. g. the logic of science) and also of the history of science and technology. Investigations on this problem may, perhaps, correspond to what is sometimes called the "theory of science," but of course, they do not exhaust all current problems of the science of science.

To have reasonable chances of success in their work for the cause of development and for the application of new methods of investigation the historians must conclude an alliance with a broad variety of specialists. This joint work must promote making the highest principle of science come true: "out, of the past, through the present, into the future."

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