

1 SYSTEMS SCIENCE AND ITS DISCIPLINES

1.1 THE CONCEPT OF SYSTEMS SCIENCE

Systems science is a new scientific discipline the subject of which is systems, and the methodology of which is the systems approach to problems. These systems are sets of interrelated elements, which may be defined with reference to natural or social subjects, may be physical or informational, concrete or abstract, existing or planned, static or dynamic, etc.

The methods of systems science are used to define systems, to distinguish them from the environment, represent them, analyse and optimize their structure and behaviour. To these ends, the methodology of new scientific fields and modern technical media are applied. Therefore, systems science is interdisciplinary and consists of the systems theory and its application.

The subjects and the methods of the various systems sciences (cybernetics, operations research, etc.) are typically so characteristic that they are often classified as individual fields of science.

The classification and terminology of systems science disciplines has been developed. Taking the aspects of water resource systems (WRS) as a technical and economic entity, we may consider the following classification:

- general systems theory,
- cybernetics,
- systems engineering,
- operations research,
- systems analysis.

The first and second fields may be classified as parts of the systems theory, the others as applications. There is no precise boundary between the subjects of these fields. Each is further categorized and uses a number of methods that have been developed into individual fields of research.

1.2 CONTENTS OF SYSTEMS SCIENCE

1.2.1 General Systems Theory

The general systems theory deals with the most general scientific principles of the existence, description and behaviour of systems. After the initial work of von Bertalanffy, 1934, 1950, 1956, it was further developed by Boulding, 1956; Ackoff, 1963;

Churchman, 1963; Mesarovic, 1963, 1964; Rapoport, 1963, 1966; and Bennis, 1962. The general systems theory includes the following subjects:

- the general systems terminology and metalanguages for the description of systems,
- the conditions of the system's existence, and its definition,
- the principle of isomorphism between systems,
- the goals and behaviour of systems,
- a comparison of methodology in natural and social sciences,
- the systems approach in physics, biology, linguistics, sociology.

Researchers approach the theory of systems so differently that distinct schools have evolved. Von Bertalanffy's approach is quite general and philosophical, it is not confined to the formalization of systems and it links the general systems theory with its applications.

On the other hand, Mesarovic, 1963, uses a formalized approach to the systems theory, and he concentrates on abstract systems (conceptual systems) that can serve as models for the whole group of concrete (real) systems, mainly technical ones, with regard to the method of formalization.

A formalized approach to the systems theory was used by Churchman, 1963, who concentrated on axiomatic construction of the general systems theory and applied it to systems optimization.

In contrast to von Bertalanffy, Ackoff, 1963, attached little importance to the investigation of isomorphisms between laws in different fields as a method of phenomena comprehension and identification. He also rejected the investigation of problems by the application of aspects of several fields as an assumption of the subsequent generalization. On the contrary, he suggested that the problem be treated as a whole and that the simpler properties be derived from the complex ones by abstraction.

The application of the ideas of Bennis, 1962, on the organization and operation of economic systems in WRS was a stimulating achievement. Bennis suggested the *multi-purpose criteria* as an index of system quality, since the system often has several purposes (e.g. the multi-purpose WRS). The systems that achieve the objectives to a required degree are considered sound systems. This method of evaluation of complex systems is promising if the required degree of achievement of the individual objectives can be defined.

According to Bennis, the *most essential feature* of a system is its ability to learn and to adapt to changes in itself and in its environment. A system which lacks this property cannot work well in variable (dynamic) conditions. Therefore, a sound system (WRS included) can monitor itself and its environment, its subsystems are governed by the objectives of the whole system, and it can adapt to internal or external changes.

Philosophical aspects are integral elements of the general systems theory. Phil-

osophy, which uses the generalisation of the results of concrete scientific inquiry as the main source of its development, inevitably deals with concepts such as “system”, “structure”, etc. Different sciences (biology, mathematics, logic, etc.) express these concepts in different terms, and philosophy tries to formulate their common essence without favouring one approach or excluding others.

From a philosophical point of view, there are two categories of systems distinguished by their different gnostic essences (Kravets, 1970), viz., real (material) and conceptual (ideal) systems. Real (material) systems are perceived or inferred from observation and exist independently of an observer. Examples of these systems are the atom, a living being, a city, a WRS, i.e. not only natural objects but also systems created by man which exist, however, not only in his mind but in reality. Conceptual (ideal) systems are symbolic structures and exist only in the mind; examples are mathematical models, axiomatic theories, the simulation water supply model of WRS, etc.

In principle, there are profound interrelationships between these two categories of systems, deduced from the fact that conceptual systems are derived, generalized reflections of material systems in the shape of models, theories, concepts and the ideas of man.

Material and the corresponding conceptual (abstract) systems are conceptually different, but their functional relationships must be the same. This relationship (analogy) is called isomorphism and the corresponding conceptual system is an isomorphic reflection of the material (real) system.

Even if the ideal reflection is not attained in the behaviour of the two categories of systems (the relationship is then called homomorphic) the differences must not exceed a certain degree, so that in the transition of the results from the conceptual system to the real one the limits of the required accuracy are not exceeded.

1.2.2 Cybernetics

Cybernetics was defined by Wiener, 1948, in the title of his book as the science of control and communication in the animal and the machine. A further definition of the concept was given by Kolmogorov, 1956. He considers cybernetics to be a science which deals with systems of any nature that are able to input, store and process information and use it for control. Cybernetics may be defined as the science dealing with behaviour and control of complex systems. As a science, cybernetics has its own subject of investigation, theory and methods.

Dynamic systems are the *subject* of investigation of cybernetics. They are studied from the standpoint of exchange of information between them and their environment, and their structure is studied from the standpoint of the exchange of information between their elements (Klir and Valach, 1965). Since man and the machine may both be elements of the systems and information may be communicated in

both directions, i.e. between people, between man and the machine and between machines, the subject of cybernetics comprises the process of information transfer and processing in automatic control systems.

Wiener's statement that the processes of communication and control in living organisms and in automatic control systems are *analogous* (not identical) is of primary significance. Therefore, both living organisms (people) and machines can contribute to the process of increasing information or to the reduction of entropy. Cybernetics is not interested in the exchange of material or the exchange of energy but only in the exchange of information both between the system and its environment and between the elements of the same system; the point is the *information approach* to the system.

The many-sided analogy between living organisms and machines in communication and the utilization of information is very important for theoretical applications, as it can be used for the improvement and perfection of technological systems and mechanisms.

Other terms that are defined include adaptivity and learning ability of the system. The living organism is able to improve itself using experience and knowledge gained. By analogy, cybernetics has raised the question: could a machine facility with a similar ability be constructed, which would mean a qualitative step in the advance of automation? Machine selfreproduction has been investigated and automata which would be able to produce more complex automata are under consideration.

The *methods of cybernetics* are related to the subject of cybernetics; they comprise:

- the theory of communication,
- information systems,
- the theory of adaptive control and learning systems,
- the general systems theory,
- analogy,
- modelling.

In systems, not the elements but their relationships are investigated by cybernetics; the question is *what the system performs*, and not *what the system is*. The response of the system to its stimuli, i.e. its behaviour, is what matters, and in this respect it has much in common with the general systems theory.

According to Ashby, 1956, cybernetics deals with all forms of behaviour, if these forms are regular, defined and reproducible. The advantages of cybernetics manifest themselves when it is applied to the behaviour of systems which are distinguished by their great complexity.

Ashby paid particular attention to those systems that are not fully accessible for direct observation, and he introduced the term "black box", derived from electronics, into cybernetics and into scientific methods generally. In the black box investigation the input and output states are the basic data. The way the inputs of the system (black box) are transformed into system output is of no interest.

Hýbl and Škabrada, 1968, considered the future utilization of cybernetics in economic and social systems. They state that in economic and social systems, man as a component is a cybernetic system with purposeful behaviour. If such a system is to function well, the different goals (interests) must be coordinated with the objectives of the whole system (see Bennis's ideas). Together with economics, scientific analysis of human behaviour (psychology, sociology) can help to do this.

Although cybernetics has developed mainly in technical systems, its achievements, general terms and methodology are also used in other complex systems.

1.2.3 Systems Engineering

Systems engineering is an applied systems discipline concerned with technical systems. Views differ both in regard to the subject of systems engineering and the methods used.

With respect to the application of systems engineering in complex WRS, the following definition seems to be adequate.

Systems engineering is an applied systems discipline concerned with the design, construction and operation of large-scale and complex technical and economic systems, using the systems approach and suitable methods of systems science to attain the optimal functioning of the system as a whole. A number of authors have put forward different definitions.

Hall, 1962, described the aims of system engineering from the standpoint of a firm: to provide information for the management for economic development, to formulate long-term objectives as a framework of the individual projects, by balancing the programs to control development in order to attain optimal use of manpower and resources, to subordinate minor projects to the overall objectives, to predict future situations and prepare the prerequisites for them, to be informed about new inventions and to secure their utilization, and to specify all operations, in great detail and with accuracy with respect to each stage of the process.

Goode and Machol, 1957, defined systems engineering as a set of problems related to the design of complex, highly automated, technical, large-scale systems.

Habr, 1970, wrote about systems engineering as an application of the systems approach in technical fields. In systems engineering the main stress is placed on the development of the concepts, and the design of a system and its implementation. Therefore, the term "system design" is encountered as an equivalent to "systems engineering". In systems engineering both the terms "optimum design" and "optimum conception" are used. They mean a design of the system such that the requirements concerning its function (objective function) are satisfied automatically or with a minimum of human intervention.

Dráb, 1973, wrote that the set of means, facilities, procedures and methods that

make it possible to satisfy the accepted criteria in research, development, design, installation, production, verification and operation constitute systems engineering.

Beneš, 1974, defined and explained systems engineering as a technique of large-scale systems concerned with design, issues of technical conception, projection, construction and operation of large-scale systems consisting mainly of non-living elements. It deals with the choice of subsystems and parts of large-scale systems so as to maximize their contribution to the required properties of the large-scale system as a whole; it is concerned with the creative design of a large-scale system, and the technical means to implement this design. In the design of large-scale systems, systems engineering is interested in technical, organizational and economic aspects.

Although comprehensive automation is one of the very important indices of technical development, in the evaluation of systems we shall direct our attention to completeness and comprehensiveness rather than to full automation. The comprehensive approach, especially, involves relatively high costs of the projects and their realization. Systems engineering, then, is used for the technical management of large projects.

The systems engineer has to be acquainted with the problems of complex systems, he needs to know how to manage a team in order to attain the objectives at the minimum cost. For this aim he has to think precisely and logically, to acquire and communicate information, to choose adequate methods for the solution of a problem, to utilize optimally the capabilities of the team and to gain its trust.

Although he may not be an expert in all the disciplines, he should have specialized in one of them (e.g. economics, water management, computer science, etc.). His most essential qualification is the ability to conceive the system as a whole in all its conditions, with the subordinate functions of the subsystems being combined to attain the overall objective most effectively ("systems thinking").

The range of methods and subjects involved in systems engineering is apparent from the book by Machol *et al.*, 1965, which deals with:

- Systems theory: the theory of information, game theory, decision theory, the simplex method, linear programming, dynamic programming, the theory of queues, Markov processes, the theory of feedback control, adaptive systems, etc.
- Systems techniques: information processing, simulation, testing of systems, economics, management of design, etc.
- Selected parts of mathematics: probability theory, Laplace's and other transformations, numerical analysis.

Sometimes all the theories and methods used in systems engineering are termed *systems analysis*, i.e. the application of the theory of systems to methods of analysis of the structure and behaviour of systems. Without specifying them taxonomically, we consider that in the design of systems, systems engineering uses all the theories and techniques that are available and can lead to the attainment of the required goal (Systems Engineering Department, 1973). Therefore, it is the methodological

framework of the approach to complex problems that facilitates the effective use of all the special modern methods.

Although the application of systems engineering has made remarkable progress in technical systems, in economic systems it is only now being introduced.

Reliability is an important factor and it should be included in the economic evaluation of technical systems. Apart from general literature (e.g. Chorafas, 1960; Calabro, 1962; Roberts, 1964; Kapur and Lamberson, 1977), specialized references are growing in number, e.g. for electronics and machinery; in water management the number of references dealing with systems engineering is relatively low (Mirtskhulava, 1974; McBean *et al.*, 1979) but this gap is rapidly being filled by publications appearing all over the world.

1.2.4 Operations Research

Operations research or operations analysis is an applied systems discipline that is used for the comprehensive treatment of concrete, technical, organizational and economic problems of complex systems. It was first used in Great Britain in 1937 as a methodological basis for air-force operations (hence the name "operations"). During World War II the operations research groups dealt with problems of supply and transportation, etc. In civil contexts, operations research has been applied to a greater degree since 1950, in connection with the development of computers.

The subject of operations research has changed from the comprehensive, systems approach to the individual development of specialized methods. Therefore its subject is well described by the definition given by Walter *et al.*, 1973: "Operations research is a set of different methods, particularly mathematical that are used for scientifically approved results, for the solution of complex economic and technical problems, especially those comprising a number of alternatives".

Morse and Kimbal, 1951, defined operations research as a special method for obtaining a good basis for decision-making in the management of operations.

Vepřek, 1970, likened the principle of operations research to the work of a research team where a group of scientists, expert in different fields, deal with the complex problem of an object that is treated as a system, using knowledge from different branches of science for its investigation.

The relationship between operations and systems analysis can be formulated by saying that operations analysis is one of the methods of systems analysis. Hitch, 1955, regarded systems analysis as an extension of operations analysis.

Most of the methods of operations research (analysis) use models preferably mathematical ones. Interdisciplinary cooperation is necessary for the development of models of complex phenomena. The models of operations research often use computers, as the treatment of many alternatives with optimization is tedious.

The following methods are used in operations research: linear programming, graph theory, simulation models, game theory, the theory of queues, inventory control models, etc. As operations research has an interdisciplinary character, the methods of technology, economics, biology, mathematics, etc. are applied.

Operations research comprises a set of different, relatively independent methods from different branches of science and it is not used for the definition and formulation of the problem. For this purpose, i.e. for the definition of the system and for forming the assumptions underlying successful treatment, the systems approach must be used (e.g. systems analysis); and for the solution of the defined problem some of the methods of operations research can be applied.

In operations research the subject is not important, it is the method used for its treatment that matters; some methods are used for a single task and other methods are preferred for repetitive application of the model.

1.2.5 Systems Analysis

The concept 'systems analysis' comprises a set of principles and methods for the analysis of the behaviour and structure of complex systems.

First, engineering systems were analysed, then economic ones. The development, methods and possibilities of systems analysis were thoroughly investigated and described in a remarkable book by Habr and Vepřek, 1972, 1986.

The concept used at the beginning of systems analysis was well defined by Hitch, 1955: "Systems analysis is a technique of investigation of military problems in a broader context and over a long-term period". Hoag, 1956, also dealt with the application of systems analysis to military research. Both use operations research as the starting-point of systems analysis.

A comparison with operations research is included in the definition by Vlček, 1968: "Systems analysis deals with relations and dependencies between tasks, the elements of decision-making and control processes that can eventually be solved and realized by the methods of operations analysis." In 1969 Vlček specified the subject of systems analysis in tasks that provide some properties and functions of the systems.

Habr and Vepřek, 1972, 1986, summarized the views of some authors into the formulation: "Systems analysis is a set of logical and formalized principles that can be used for the effective combination of partial resources with corresponding knowledge for an effective attainment of the given goals." They classify the approaches of systems analysis in dealing with problems into three categories:

- systems analysis of real systems,
- systems analysis of information systems,
- systems analysis of control systems.

Systems analysis of real systems is suitable for the design of engineering systems, including the WRS. The analysis of several alternatives is used for the determination of an optimal design. Such a concept of systems analysis is very close to systems engineering. The military organizations (e.g. RAND in the U.S.A.) and the manufacturers of computers focus their attention on this concept. Vito-Don, 1967, applied systems analysis to problems of cost-benefit analysis.

Systems analysis is also applied in the design of *information systems*, assuming that the requirements to be met by them are specified by the management system. A well designed management information system should eliminate incomplete, redundant and irrelevant information. It should be suitable for long-term and short-term planning, for operations control and analysis of the behaviour of the system and it should provide an idea of the state of the object; this idea should be given in time, space and quality so that the decision-makers and managers can utilize it easily.

Systems analysis of control systems is applied in economic and technical subjects. Hare, 1967, defined three stages of systems analysis:

- the definition of the system,
- the analysis of the structure and behaviour of the system,
- the design of the system or its improvement and implementation.

In 1974, the Institute of Management answered the question of what applied systems analysis is in this way: "Applied systems analysis is not only a technique or a group of techniques such as the theory of probability or mathematical programming. It is a framework that is to aid the decision-makers in choosing an adequate (in some cases the best) way of action. Applied systems analysis is used for concentration and intensification in dealing with large-scale and complex problems. Applied systems analysis is a general term including fields like operations research, decision theory, cost-benefit and efficiency analysis; planning, programming and scheduling, design analysis; many aspects of cybernetics, the theory of information, artificial intelligence in management and information systems; dynamic modelling, the theory of behaviour, decision-making; the theory of organization."

Applied systems analysis is included directly in the name of IIASA (International Institute for Applied Systems Analysis). The range of the fields and problems contained in applied systems analysis is apparent from the research programme of this institute, which includes:

- resources and environment: ecological problems, problems of water resource research, problems of food and agriculture, etc.,
- human settlement and services: problems of population, health, education, communication, etc.,
- management and technology: man-made artifacts, institutes, economic systems, technologies, etc.,
- systems and decision sciences: mathematical and computational problems in the analysis of large systems, etc.

Among the fields included in the framework of systems analysis, *decision theory*¹⁾ provides methods showing how to choose in decision situations from a set of feasible decisions the scientifically approved optimum decision, and thus it is very important for WRS.

In decision theory, the methods of optimization, probability theory, mathematical statistics, utility theory, reliability theory and theory of games are applied in the first place.

Although mathematical methods are applied in the selection of the best decision or optimum alternative, a strong subjective component remains, and in many cases decision-making is not only a science but an art.

In a decision situation one or more participants are involved who are influenced by the consequences of the decision. According to the nature of these consequences, the decision situation may be either competitive (conflict) or bargaining (non-conflict). The *non-conflict situation* can arise if only one participant and a single consequence of a certain decision are involved. The mathematical method for this basically simple case of decision-making is often mathematical programming (linear or non-linear programming).

For WRS the second case is more interesting, i.e. when the decision is influenced by various participants and the *situation is competitive (conflict)*.

A survey of types of decision situations was given by Mañas, 1974, in a book on game and decision theory.²⁾ The theory of games is a promising technique for the treatment of problems in WRS.

In the decision process the following steps are applied:

- 1) The *goal* is determined (attainment of certain parameters, risk or reliability, the requirement of environmental quality, etc.)
- 2) A list of all the feasible *alternative solutions* is constructed. A creative imagination is necessary for the definition of the feasible alternatives, and professional knowledge is required to omit the evidently non-effective alternatives from the list.
- 3) A list of *factors* (technical, economical, intangible, etc.) that influence the decision is made out. The danger of omitting an important factor is greater than omitting a feasible alternative.
- 4) The *number of alternatives* is reduced by an analysis of the important factors.

¹⁾ As analysis of real systems is sometimes assigned to systems engineering, decision analysis is sometimes included in systems analysis. The first books on decision analysis as a specific scientific field appeared in the fifties: Luce and Raiffa, 1957; Chernoff and Moses, 1959; Weiss, 1961; Dyckmann, McAdams *et al.*, 1969; Lee, 1971, etc.

²⁾ Important initial references to the theory of games are Blackwell and Girshick, 1954; Karlin, 1959; McKinsey, 1952; von Neumann and Morgenstern, 1944. The book by Mañas, 1974, has 357 references and one of them, "Contributions to the Theory of Games" (Princeton University Press, 1959), includes more than 1000 references up to 1958.

This stage may be influenced by subjective views as estimates have often to be used (the art of decision-making).

5) The *number of factors is reduced* in relation to the remaining alternatives.

Using the results of these five steps we continue the analysis (if the results are satisfactory) or we try to find the reasons for the unsatisfactory results (oversimplification, or, on the other hand, an over-complicated model).

The *reliability* with which the system functions is its most important characteristic. A numerical value for this is obtained by the mathematical methods of probability theory, and mathematical statistics. Direct application of their outputs, however, can result in a situation that is far from reality. A scientific analysis of the phenomena is necessary and in complicated cases a heuristic approach is recommended.

The reliability, however, retains, its probability character, and it can be defined as the probability that the system (or its element) will, under given conditions, satisfy the requirements in a certain time period.

Most mistakes in the definition of reliability pertain to the idea of the long-term stability (constant value) of reliability, although this changes with time (it is time dependent) for various reasons; e.g. due to worn-out parts in some devices, or due to changes in water demand in water systems, etc.

An important index in the computation of reliability is the risk of failure of the system (or its elements). It can be expressed by a probable number of failures in a time unit (occurrence-based reliability), the duration of failures (time-based reliability) or the volume of deficits in production (quantity-based reliability).

The more complicated cases of reliability determination are derived from the coordinated functioning of several elements in the system with different reliabilities and with different relationships between them. The greater the number of elements in the system, the operation of which is necessary if it is to function correctly, the lower the total reliability. Therefore, the problem increasing system reliability is often dealt with in theory. The tools for achieving this increase may be:

- the installation of slack facilities or their parts (“redundancy”),
- simplicity of the structure,
- the use of standard and reliable parts,
- reduction in design load.

In decision-making generally, two questions may be raised:

a) How would an average person decide in a given situation? (e.g. what response in consumption can be expected from the inhabitants after the installation of a new water supply, what response in water deficits can be expected, etc.?)

b) What is the best decision in the given situation?

In WRS view b) is often applied which should lead to a logically correct decision. Of course, this approach to decision-making cannot eliminate the impact of subjective views and the intentions of the participants. The theory of games also includes these relatively frequent cases.

1.3 DEVELOPMENT OF SYSTEMS DISCIPLINES

In many scientific disciplines, the modern views were formulated 2500 years ago by the Greek natural philosophers on the basis of mere philosophical speculation. Similarly, the systems approach to a perception of the world which embraced its evident and hidden relationships was discovered and formulated. An outstanding place belongs to Pythagoras and his School, which constructed an interpretation of natural science, analysis, the wholeness of the natural world and its relationships in mathematical terms. A present-day formulation might be: Pythagoras' School tried to create a mathematical model of the world and numbers took the place between things and ideas (Volkov, 1975).¹⁾

The use of feedback control in irrigation systems (Institute of Management, 1974) has a 4000-year-old tradition. By irrigation of the land with water from the Euphrates and Tigris Rivers the old Babylonians achieved such a high degree of efficiency in agricultural production that it provided for the highest population density at that time. Using feedback, they controlled the moisture of the soil by opening and closing irrigation channels. One of the 282 laws in the Hamurabi's Code (approx. 2100 BC.) stated: If anybody opens the irrigation channel but is negligent, and water flows to the land of his neighbour, he will pay for the loss of corn. This can be qualified as the first known statement of a legal fine for negligence on the part of a human operator in a feedback control system.

The realization of artificial, relatively complex engineering systems is related to machine production. The systems machine technology was accompanied by the development of systems characteristics in scientific research. As soon as the engineer, biologist, economist or any other expert begins to realize that the mutual structural and functional relationships between the subjects of investigation form a whole, he has to think in systems terms, taking into account the relationships in his own field. If he does not do so, his reasoning is not comprehensive, the conclusions may not be complete and, consequently, not correct.

The nature of the issues in different scientific spheres influenced the earlier or later use of the systems approach. For example, ponds are generally isolated elements and therefore, in their design and operation, the relationship between them need not be considered. However, the designers of the old *systems* of ponds in the 16th century had to take into account the structural and functional relationships between individual ponds. For example, the levels of the ponds in South Bohemia (Czechoslovakia) which were fed by the Golden Canal were dependent on the water level

¹⁾ An interesting study of the interpretation of the systems approach in scientific knowledge was carried out by Ogurcov, 1974. He dealt with the ancient concepts of the characteristics of existence and recognition, using contemporary systems ideas in ontology, and with the interpretation of systems attributes of scientific knowledge in the philosophy of the new era, especially in classical German philosophy.

in the Canal and changing the levels during fish-harvesting operations had to be coordinated.

Much closer interrelations exist in the systems and cascades of modern reservoirs. The first dams were designed as isolated items (although at the beginning of the 20th century a flood control system of reservoirs was designed and built on the Nisa River). The modern reservoirs are the elements of a WRS with cascades from reservoirs on the same river or on different watercourses (e.g. WRS for the water supply in the Ostrava region see Chapter 12).

Such an attempt at the comprehensive treatment of problems by considering interrelationships was repeated in other branches of science, too. Habr and Vepřek, 1972, cited a number of economists (Quesnay, Marx, Keynes, etc.) who were conscious of the necessity to treat problems comprehensively. They state that there is a gap between those attempts to use a systems approach and the possibility of applying it in economics; these earlier economists did not have the appropriate methods and technical means for real systems work. However, a comprehensive systems treatment of economic problems is still more of a wish than a reality. In water management the situation is similar, and technical parameters are often used instead of economic ones.

So far, the reservoir has been considered as an element of the system. If a more detailed discriminating level is used, the dam (i.e. a part of the reservoir) can itself be treated as a system. Its elements are the embankment of the dam, spillway, outlets, diversion channels, etc. If an engineer designs the reservoir as an isolated structure, i.e. without the necessity of the systems approach in relation to other reservoirs, he has to deal with a component part – the dam – as with a system of elements with structurally and functionally dependent variables (conception of design and construction; relationships given by the release of water and withdrawals).

Another example of WRS is the River Váh cascade in Czechoslovakia. There are clear structural relationships there (e.g. between the water levels in the reservoirs – the elements of the system) but functional relationships are also evident (e.g. the time-related operation of the subsystems). The exploitation of the River Váh for hydroelectric power generation would not have been possible without a systems approach.

The oldest WRS structures are the systems of ponds in Bohemia and Moravia¹) and the water-supply system for mines in Slovakia¹) (14th – 17th centuries).

The interrelationship between different forms of surface water (i.e. watercourses, lakes, etc.) and ground water required the systems approach very early in history for a comprehensive use of water resources and their conservation. A well-known historical system existed in Solomon's ponds in Jerusalem (10th century B.C.) and there were some older irrigation systems in ancient cultures.

¹) Czechoslovakia (ČSSR) consists of three geographical units: Bohemia, Moravia and Slovakia. Bohemia and Moravia form one part of the federation (ČSR) and Slovakia the second part (SSR).

Although the systems approach has been applied in scientific and engineering problems since ancient times and the necessity for it has become more and more evident, the origin of “systems sciences” dates from about 50 years ago. The growing complexity of systems and their problems required the formulation of general methodological principles for their definition and treatment.

The *general systems theory* is one of the modern gnostic approaches to the investigation of complex subjects. The Austrian biologist Ludwig von Bertalanffy was the founder of this new branch of science. In the thirties he developed the theory of open systems in biology and, around 1950, the principles of the general systems theory. In 1954 he was one of the founders of the Society for the Advancement of the General Systems Theory (renamed the Society for General Systems Research, an affiliate of the American Association for the Advancement of Science). Every year, this society publishes thick yearbooks (Yearbook of the Society of General Systems Research, University of Michigan, U.S.A.) with contributions not only on the general systems theory but also on its application in many spheres.

Lektorsky and Sadovsky, 1960, considered the von Bertalanffy theory of open systems to be an important philosophical and methodological achievement, synthesizing the tendencies in modern science. In this respect, it can be compared with the work of other outstanding progressive scientists, e.g. Wiener, Ashby, etc.

As far as WRS is concerned, it is open systems which are significant, i.e. systems with input and output, with stimuli and response, as opposed to closed systems, which have no input and output. The Belgian Prigogine, 1947, 1955, classified systems in three categories – open, closed and isolated. Isolated systems will not be discussed here as they do not exchange either matter or energy with their environment and, in fact, do not exist in nature.

Von Bertalanffy, 1962, considered the theory of open systems and states of dynamic equilibrium as a generalization of physical chemistry, kinetics and thermodynamics. The general systems theory was a further generalization. He mentioned it for the first time at the philosophical conference in Chicago, 1937, but he decided to publish it only after World War II when he found that other scientists were also using this special way of reasoning.

The investigation of living organisms as an open system with processes of exchange of matter with the environment has resulted in a new concept, which is also used in WRS, i.e. the notion of “homeostasis”. It appeared in the publications of the American physiologist Cannon, 1929, who studied the control mechanisms which maintain the blood composition of mammals. However, homeostasis is a set of processes which maintain an inner equilibrium state of the system. For all the phenomena which protect the cell and the living organism from the effects of the environment and keep them stable, Heilbrunn, 1956, introduced the concept of “biostasis”.

The beginnings of systems science can be found in the thirties. The rapid methodological development of this science occurred in the fifties and the main achievements

of its applications at the beginning of the sixties when computers provided the necessary technology for the solution of complex system problems.

At the present time, there is continuous development of a number of relatively independent scientific fields relating to the treatment of systems problems, sometimes with varying definitions of the subjects¹⁾.

¹⁾ Let us try to sum up the development of the methods used in the treatment of systems up to the time of publication. A list of selected publications follows. Classification is according to the fields comprised in the systems science, its adjoining or related spheres, or its applications (in this part the name of the author and the year of publication do not necessarily mean a quotation or reference):

a) *In the field of general systems theory:*

- general systems theory (von Bertalanffy, 1950, 1956, 1958; Boulding, 1956; Ashby, 1958; Mesarović, 1963, 1964; Ackoff, 1963; Rapoport, 1963),
- general systems theory in scientific methodology (Boulding, 1956; Mesarović, 1964),
- mathematical systems theory (Wymore, 1967; Kalman–Falb–Arbib, 1968),
- theory of open systems (von Bertalanffy, 1950),
- theory of open systems in biology (von Bertalanffy, 1950),
- theory of control (Mesarović, 1963; Godunov, 1967),
- theory of optimal control (Kalman, 1958; Neustadt, 1960; Lee–Markus, 1961; Pontryagin *et al.*, 1961),

b) *In the field of cybernetics:*

- cybernetics (Wiener, 1948; Ashby, 1956; von Bertalanffy, 1962; Maruyama, 1963),
- cybernetics in air-defence artillery (Wiener, 1961),
- algebraic theory of machines (Riguet, 1951; Krohn–Rhodes, 1965, 1968; Hartmanis–Stearns, 1966),
- theory of automata (Rabin–Scott, 1959; Arbib, 1965, 1969; Dakajev *et al.*, 1970),
- theory of abstract automata (Arbib, 1969),
- theory of adaptation (Ashby, 1940; Mesarović, 1963),
- theory of regulation (automatic control) (Ashby, 1956; Kalman, 1958),
- theory of groups (Kurosh, 1953; Hall, 1959),
- topology (Bourbaki, 1951; Leeman, 1962; Langefors, 1966),
- information theory (Shannon, 1948; Goldman, 1953; Khinchin, 1954; Kolmogorov, 1956),
- information theory in psychology (Attneave, 1959),
- mathematical theory of communication (Shannon–Weaver, 1949),
- communication theory in secret systems (Shannon, 1948),

c) *In the field of systems engineering:*

- systems engineering (Goode–Machol, 1957; Hall, 1962; Chestnut, 1967),
- systems programming (Habr, 1965),
- decision theory (Chernoff–Moses, 1959; Raiffa–Schlaifer, 1961),
- engineering psychology (Lewin, 1936),

d) *In the field of operations research:*

- operations research (Morse–Kimball, 1951; Churchman–Ackoff–Arnoff, 1957),
- graph theory (Euler, 1736),
- network analysis of complex activities (Berge, 1958; Ford–Fulkerson, 1962),
- structural analysis (Vepřek, 1970),
- econometrics (Tinbergen, 1957),
- mathematical economy (Baumont, 1961; Nemchinoff, 1964; Mansfield, 1966),
- the theory of queues (Got–Smith, 1961; Saaty, 1961; Kaufman–Cruon, 1962),
- the theory of replacement (Cox, 1962),

Systems engineering, for example, was developed from industrial engineering with specific objectives and methods of organization of work. According to the definition of its subject by the committee for standardization of A.S.M.E. in 1943, it was close to the contemporary economics of industrial sectors. It also included optimization of benefits and minimization of risk in business.

With the growing complexity in business economics the systems approach to business firms and their environment was applied. As a result of this modernisation of views and methods, industrial engineering is approaching systems engineering which uses this new scientific method to assist in the management of complex industrial organizations. New systems are being modelled, old systems have been analysed and improved. In addition, the time intervals between a scientific discovery and its application and between the origin of the demand and its satisfaction have been reduced (Hall, 1962).

The concept “complexity”, as it appears in different branches of human activity, has become a problem of integration:

- in transportation (the coordination of enormous quantities of goods by different means of transportation with large-scale capacity on an international scale),
- in communications (the automatic long-distance and international telephone systems),
- in water management (the long cascades of extensive multi-purpose WRS, with different water demands and different reliability requirements creating many inter-relationships in the system),
- in industry (the big trusts, monopolies, etc. as complex and comprehensive economic production systems with combinations of automatic control and operation by human beings),
- in trade (large-scale information systems with modern computer hardware and software),
- in military contexts (the extensive military systems provided an impetus to the application of new scientific disciplines to complex problems),

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- the theory of games and strategy (von Neumann–Morgenstern, 1944, 1947; McKinsey, 1952; Blackwell–Girshick, 1954),
 - inventory theory (Moran, 1959; Heady–Within, 1963; Morse, 1958),
 - factor analysis (Spearman, 1904).
 - e) *In the field of systems analysis:*
 - systems analysis (Hitch, 1955; Hare, 1964, 1967; Vlček, 1968),
 - systems analysis in military research (Hitch, 1955; Hoagh, 1956),
 - systems analysis in the air force (Churchman *et al.*, 1957),
 - systems analysis in the field of management and control (Johnson *et al.*, 1963; Modin, 1963; Hare, 1967),
 - systems analysis in data processing (Langefors, 1966),
 - systems analysis in computer science (McMillan–Gonzales, 1968),
 - systems analysis in effective planning (Rudwick, 1969).

– in science (modern science is often associated with high costs but also with complexity in organization).

This integration of problems creates a demand for a new type of experts (systems engineers) who are able to synthesize the design and operation of large-scale and complex systems.

Science itself is, in fact, a complex and dynamic system and can therefore be the subject of systems analysis. Its elements may be chosen according to the standpoint of investigation (Kedrov, 1974):

- objects if gnostic objects matter,
- methodology if the way of cognitive analysis is most important,
- subjective goals if specific practical aims of scientific research are discussed.

The gnostic *object* is formed by a system of natural, and other sciences: the first group comprises the subsystems of mathematics, physics, mechanics, chemistry, biology, etc.; the second group consists of the social and economic sciences, philosophy, psychology, linguistics, etc. In addition, interdisciplinary sciences have been established including systems science (cybernetics, etc).

In the course of investigation not only objective but also subjective views occur. The abstract reasoning used in methods of investigation depends on the subject employing it.

The achievement of the *goal* of investigation and its *practical* utilization is even more closely related to the human being in question – the human subject.

Pure (“classical”) sciences correspond more closely to the objective aspects of science, whereas applied sciences correspond to the subjective ones (e.g. purpose, goal).

The technical sciences straddle the line between the natural and social sciences as their goals are formed by social conditions but the achievement of these goals depends on natural laws. The new science of science (metascience) deals with science as an object of investigation. Of course, in this science the systems approach is utilized with the following concepts: the model of science, structure, mathematical models of scientific research, etc.¹⁾

The survey of scientific fields and references shows that extensive development of systems science began in the fifties. In Czechoslovakia systems references have been appearing since the sixties (Habr, Beneš, Kamarýt, Kubík, Kotek, Korda, Dráb, Walter, Vlček, etc.) and a reference to its application in water management appeared in 1967 (Kos, Partl). The development of systems science is characterized by special organizational and professional activities.

In 1954, as stated, the Society for the Advancement of General Systems Theory was founded in the U.S.A. The International Association for Hydraulic Research

¹⁾ Systems analysis issues featured prominently in the yearbook “Sistemnyye issledovaniya” (System research) published by Nauka, Moscow.

(IAHR-AIRH) was founded in 1935, and one of the eight committees under its direction is the Committee on Water Resources Systems, set up at the end of the sixties. WRS problems were also included among the main topics of the 15th Congress of IAHR in 1973.

The issues of water management are the concern of IWRA (International Water Resources Associations), which in 1973 organized its First Congress in Chicago under the slogan: “*Water for the Human Environment*” and a Second Congress in 1975 in New Delhi under the slogan “*Water for Human Needs*”. The worldwide problems of water management were raised as early as in 1967 by the United Nations, which organised a conference “*Water for Peace*”, which was attended by the U.N. member countries.

Since 1973, there has been working International Institute for Applied Systems Analysis (IIASA) in Laxenburg (near Vienna, Austria) (preparatory work started in 1967); the founders of the institute were institutions in the Soviet Union, Canada, Czechoslovakia, France, German Democratic Republic, Japan, Federal Republic of Germany, Bulgaria, the United States of America, Italy, Poland, the United Kingdom. By 1977, Austria, Hungary, Sweden, Finland and The Netherlands had all joined. In its Charter, IIASA laid down the following objectives:

“The Institute shall initiate and support collaborative and individual research in relation to problems of modern societies arising from scientific and technological development. To this end, the Institute shall undertake its own studies into both methodological and applied research in the related fields of systems analysis, cybernetics, operational research, and management techniques.

The Institute shall encourage and reinforce national and international efforts in corresponding fields of inquiry; devise means of enhancing appreciation of this type of research among scientists from all nations; and attempt to increase understanding through the development of uniform standards and terminology. Its work shall be open to all experts in conformity with the normal practice of international scientific co-operation.

The Institute’s work shall be exclusively for peaceful purposes.”

IIASA has directed its research program towards methodology, big organizations, integrated industrial systems, urban and regional systems, ecological systems, biological and health problems, computers, energy, water, etc. IIASA uses a matrix organization with four divisions: Resources and Environment; Human, Settlement and Services; Management and Technology; System and Decision Sciences; and two programs: Energy Systems and Food and Agriculture.

In Resources and Environment comprehensive research of WRS was carried out at three levels: *Level I* – the problems of local water reservoirs and lakes, water storage and distribution, operation of WRS, short-term operation; *Level II* – the problems of large regions, long-term operation, e.g. large-scale investment in water resources and long-term development plans; *Level III* – global problems, e.g. global

air and water pollution, the global scarcity of fresh water resources.

In Czechoslovakia, since 1971, a WRS subcommittee of the Committee for Water Management of the Czechoslovak Academy of Sciences has systematically investigated the problems of WRS and has helped in the systems approach in all the main tasks.

In the Water Management Association of the Czechoslovak Association of Engineering and Science a new group has been established for WRS.

The concentration of Czechoslovak water resource engineers and scientists on the problems of WRS resulted in numerous studies, publications dealing with WRS, case studies, a special chapter in the General Water Plan, 1976, and the organization of five special symposia on WRS.