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# Management and Modeling in Transport Systems using Self-Organization

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## Abstract

The paper is devoted to the presentation of directions for the application of self-organization in the management of processes and structures of railway transport. The key provisions regarding the author's theoretical development of self-organization - a unified theory of self-organizing systems - are formulated. Three sources of the formation of a unified theory of self-organizing systems are provided: the general theory of systems by L. von Bertalanffy, the theory of functional systems by P. Anokhin, the theory of fuzzy sets or the theory of tolerant sets by L. Zade. Six basic principles of self-organization are described. Practical developments of the theoretical provisions of self-organization are presented. A method of detecting hidden statistical regularities in the management of the traffic safety process in railway transport is proposed. A method of systematizing cases of traffic safety violations based on nine parameters, signs and the sequence of identifying bottlenecks in the safety management process is proposed. The norm of behavior of the self-organizing system is determined. A set of simulations using Volterra and biocenosis models is also presented. This complex is proposed to be used in the analysis, assessment and forecasting of the functional and structural development of the transport system in order to maintain a stable balance of functioning.

**Keywords:** principle of self-organization, environment, transport technologies and systems, system approach, "bottlenecks", norm of system behavior, system development, final result of activity.

# 1 Introduction

Self-organization is a comprehensive concept that is characteristic of almost all areas of human knowledge and practical activity. The principles of self-organization under various names are intuitively or purposefully implemented in the management of technological, biological, social systems and projects. Interest in self-organization can be explained by many factors, including:

- the scale of integration and disintegration (knowledge, structures, formations, coexistence of the global world and states - "dwarfs");
- ongoing transformations (of states, large companies, concepts);
- virtually inexhaustible capabilities of the Internet and digital systems in supporting decision-making, which allows an individual to use unlimited resources to solve individual tasks;
- the development of digital technologies or the fourth stage of scientific and technical progress led to the implementation of complex tasks with the help of a gadget, the development of unmanned technologies, the practical implementation of artificial intelligence - a key component of the self-organization process;
- the concept of risk and permanent crisis situations have become the main features of life and activity of man and humanity. This required a new view and systematization of the management problem.

The article is devoted to the directions of using the theoretical provisions of the universal mechanism of self-organization, which were called the unified theory of self-organizing systems (presented in the book [1]) and the directions of its practical implementation in transport technologies and systems.

The viability of the transport system is characterized by its ability to maintain a stable equilibrium state in interaction with the environment. This ability is called adaptation. The essence of adaptation is the constant search for options for a successful solution to the problem of maintaining a stable balance.

Sections 1.1-1.3 are devoted to the presentation of individual concepts of the unified theory of self-organizing systems. These concepts obtained from the study and analysis of various scientific fields (biological, natural science, mathematics, social, cybernetics, etc.). Features of self-organizing systems are (a) the unity of the object and its environment, (b) they are open and require a systematic exchange flow of energy and matter from/to the environment to ensure a stable equilibrium state.

### 1.1 Theory of systems and system approach

The peculiarity of the approach of L. von Bertalanffy in the general theory of systems (further - GST) consists in the classical interpretation of the structural organization of functional systems - a traditional anatomical principle that reflects the orderliness of specialized classes of phenomena of a living organism and studies the mechanisms of vital activity of individual organs in the dynamics of their work [2]. In GST, L. von Bertalanffy developed a mathematical apparatus for describing different types of systems, which allowed it to be used in various fields of knowledge. GST summarizes exclusively voluminous material from biological, social and exact sciences. The introduction of the concepts of "autonomous" system and "interdependent" system revealed the problem of levels of system organization. At the same time, the question of the "paradox of development" was raised. GST reveals the essence of the structural formation and development of the system, but does not provide an explanation of the mechanism of formation of system elements.

Almost at the same historical time, the theory of functional systems (further - TFS) by P. Anokhin arose. In TFS, a system is a complex of selectively involved components, the interaction and relationships of which lead to a useful final result. TFS has become a systems approach for biology, cybernetics and engineering. The fateful participation of the system elements in obtaining the final result is justified depending on the conditions of change of adaptation and compensatory processes of maintaining the equilibrium state of the system in interaction with the environment. TFS proves the continuous mobility of the fateful contribution of elements in the formation of the final result, seeking to minimize costs for its achievement. The dynamism of the structural and functional transformations of the system is perceived as the universality of the behavior stereotype. The representation of dynamism also extends to the concept of norm. In fact, the norm appears as a dynamic stereotype that continuously interacts with the statistically determined behavior of an organism (object or system) in the environment. Given the norm, the body forms adequate reactions to changes in the environment. Based on the principle of invariance and similarity, it can be argued that the mechanism of behavior of the man-machine system and any self-organizing system in general is similar to what was described by P. Anokhin in TFS. The final result reflects the degree of adaptation of the system to changes in the environment.

Later, the systemic approaches described above were developed in synergetic (for example [3], [4]), the method of detecting hidden statistical regularities [5], the theory of dynamic management, sociology, etc.

### 1.2 Tolerant spaces

In TFS there was no solution to the problem of uncertainty of environmental change and sufficient mobility of a dynamic stereotype of behavior. The solution to this problem was proposed by L. Zadeh. The solution was named fuzzy set theory (FST) [6], and later - the theory of tolerant spaces.

L. Zadeh considered his theory as an apparatus for analyzing and modeling humanistic systems - systems in which human knowledge and judgment play a significant role. In FST, the elements that determine the final result are not specific numbers, but some fuzzy variables, in which the transition from "yes" (belonging) to "no" (non-belonging) is not jump-like, it is continuous. Recently, the humanistic system is called a man-machine system, and a more generalized version is called a "man - control object - environment" system.

The size of the rating scale unit from "yes" to "no" creates inaccuracy in the definition of the concept of "sameness" or "similarity". With small values of the scale unit, you can successively go from "yes" to "no" without marking the difference. Such a process corresponds to the principle of tolerance in mathematics. The sense of difference arises as the scale unit increases, which is due to the summation effect of the accumulation of errors.

### 1.3 Principles of self-organization

The general principles of self-organization of functional systems include the following principles:

- *Pr.1: self-assembly of the system and conditions of its existence*. In other sources, it is interpreted as "the unity of the object and the environment", as well as the principle of complementation. Stable relations between the system and the environment do not create conditions for the reorganization of the system, so the management process is related to maintaining its maintainability. A change in the environment should lead to an adequate change in the interaction of system elements and their influence on the formation of the final result. However, a fixed number of changes are allowed. The mechanism of adaptation to changes in the environment is the final result of the system's activity;
- *Pr.2: dichotomy*, which is also called unity and struggle of opposites, ambivalence, symmetry. The principle insists on the simultaneous presence of factors that support or hinder the equilibrium of the system with the environment. Both factors are important to maintain optimal condition;
- *Pr.3: isomorphism of the organization of functional systems* of different nature and levels;
- *Pr.4: variability and statistical formation of the final result*. This principle states that to obtain the same value of the final result, different values of the elements of the system are possible. A set of different interrelationships of system elements, but with the same final result, form equipotential states of the system;
- *Pr.5: the smallest action* helps to choose the most economical way to achieve the final result. This principle corresponds to the general law of the natural environment - the desire for an optimal structure, which is dictated by life circumstances: to ensure the necessary functioning with a minimum of energy costs;
- *Pr.6: of a bottleneck*, says about the existence of a weak link in the system and insists on actively using the potential to strengthen this link.

All the above principles are used in self-organization systems. But some principles are general, and some play a key role in practical use. This will be indicated in sections 2.1 and 2.2.

The variety of interpretations of the principles is explained by the variety of scientific knowledge and their characteristic terminology. The commonality of their semantic content confirms the conventional concept of A. Poincaré about the conditional division of science into separate fields of knowledge.

## 2 Management of a transport process or structure

For the purpose of managing processes and structures, the Method for detecting hidden statistical patterns (hereinafter referred to as the Method) is proposed. It is

based on the use of key principles: Pr.1, Pr.3, Pr.4, and Pr.5, which are given in 1.3. This Method is adapted to the management of the railway traffic safety process.
Let's define the characteristic points of the Method.

Signs of determining bottlenecks
Sign 1 – “outlier” of the violation statistics parameter for the period of analysis (Fig. 1).

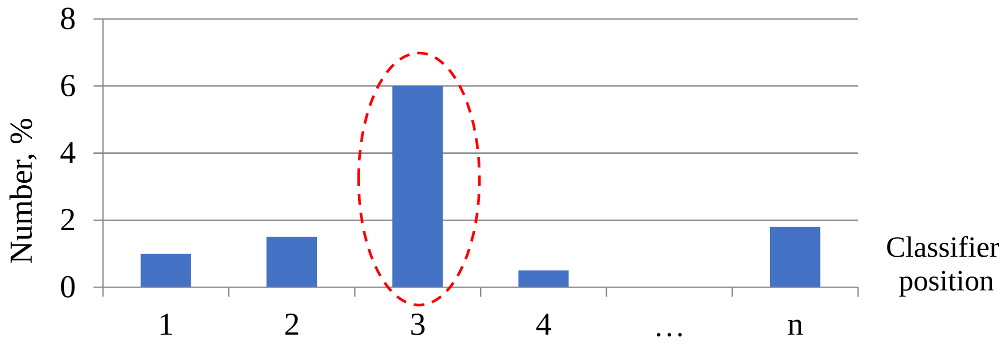


Figure 1: The first sign of a bottleneck is "outlier".

The red stroke in fig. 1 marks the "bottleneck" of the first feature, n is the number of elements of the statistics parameter.
Sign 2 – "negative trend" of the dynamics (time series) of changes in the analyzed statistics parameter in adjacent time periods (Fig. 2).

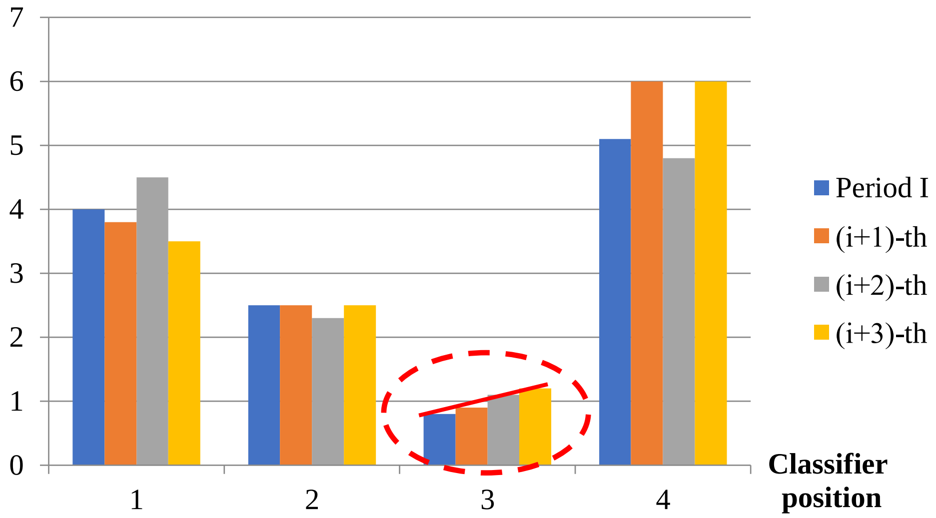


Figure 2: The second sign of the bottleneck is the "negative trend" (marked with a red stroke) for four periods of control.

If, on the basis of the graphical representation of the registered parameters, a uniform manifestation is observed (that is, there is no pronounced bottleneck), then sources of improvement of the situation should be sought in the plane of the organization of the technological process.

There may be several bottlenecks.

*Systematization of transport system activity information*

Statistical activity information is used to manage transport systems. The problem of using statistical information is the verbal way of their presentation. Therefore, to use statistical methods of management, verbal information must be formalized or systematized.

For safety management, we will use the statistics of refusals and violations of transportation regulations as they are formed in a specific railway company.

The method suggests presenting each refusal in the form of answers to nine questions or in the space of nine parameters (Fig. 3).

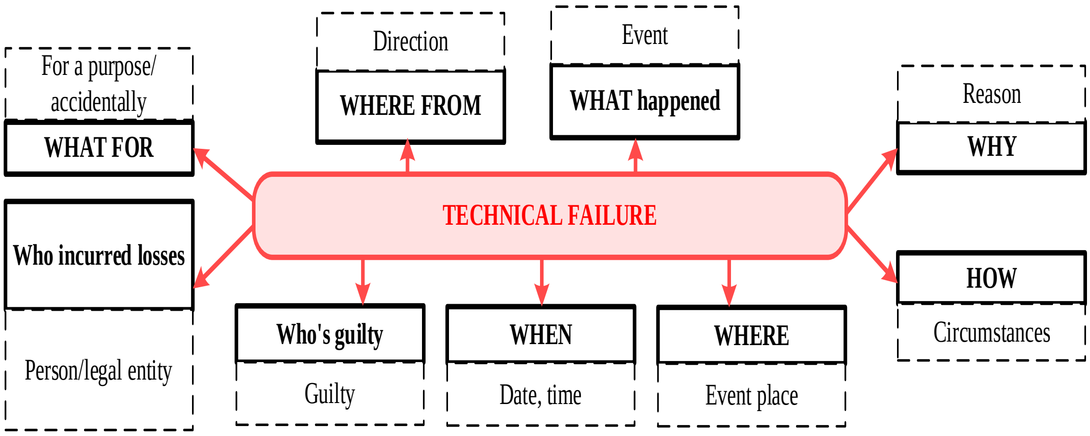


Figure 3: Systematization of cases of statistics of failures of technical means of railroad automation.

The "WHAT" parameter characterizes the event according to the existing transport event classifier. The geographical location of the event (station, precinct, crossing) is evaluated using the "WHERE" parameter. The "WHEN" parameter is the time of the event. Circumstances ("HOW") contains a qualitative description of the event: information about the train (train number, number of cars, tonnage, number of axles), locomotive, cars, weather conditions, state of rolling stock, state of infrastructure, compliance with the traffic schedule, state of health of the locomotive brigades, etc. The "WHY" parameter is a possible reason. "WHO" is the violator (it can be a person or a structural unit of railway transport). The answer to the question "WHAT FOR" contains information about the intentionality of the event. The parameter "Who incurred" should contain information about the consequences of the loss. "WHERE FROM" is the direction of movement.

*Identifying regularities*

is carried out by graphically constructing the following dependencies:

a) variations of individual systematization parameters WHAT, WHERE, WHEN, ... (Fig. 3) over time;

b) variations of the constituent parameters of systematization over time;

c) in the space of two and three parameters of systematization (for example, WHAT - WHERE, WHY - WHEN, WHAT - WHO - WHERE, ...).

*The norm as a functional optimum*

The term "norm" has a key character in the Method. Today there is no established concept of the norm. The statistical average (population or "generalized") norm for a set of phenomena, objects or people cannot correspond to the norm of a specific process, structural unit or person.

The functional expediency of achieving the final result of the process forms a stereotype of system behavior under stable relations with the environment or a norm of behavior. Changes in relations with the environment lead to the evolution of the system and norms. In case of loss of stability, the system is transformed or destroyed. In this, its orderliness in the environment disappears.

The norm determines the characteristic of the parameter of the final result based on the statistics of this parameter. The norm is both a process and a quantitative characteristic. But in quantitative terms, this is the range of values of the parameter of the final result, which characterizes the optimal relationship of the process or structure of railway transport with the environment.

There are two points beyond which activity becomes unprofitable. These points correspond to the inflection points of the normal curve statistics of the final outcome parameter of the process/structure, i.e. $m \pm \sigma$, where m is the mathematical expectation of a normal distribution and $\sigma$ is the standard deviation. The range defines the zone of functional optimum, when it is possible to maintain the equality of acquisitions and losses. Approaching these points from the m side should cause alarm and take measures to stabilize the condition. This is how a condition is established in the links of the railway system, in which it is necessary to apply measures of increased concern. Because beyond these points, there is a discrepancy between the capabilities and needs of the railway industry, its individual link or section.

Thus, the norm (norm of system behavior) is:

a) the process that determines the optimal mode of functioning of the system in interaction with the environment, that is, the functional optimum;

b) the interval of optimal functioning of the system with variable boundaries, in which the optimal connection of the system with the environment and the coordinated performance of all its functions are preserved.

Norm-based control is a constant refinement of the boundaries and center of the functional optimum as statistical data on the state control parameter accumulate.

The norm is influenced by the environment and therefore changes during the life cycle. Analyzing the location of the norm, the amount of dispersion and the speed of their change, it is possible to predict the state of the system and determine its adaptive capabilities.

*Technique of applying the Method*

The sequence of application of the Method of detecting a hidden statistical regularity (methodology) was developed, which is given below:

1- detection of violations of traffic safety regulations, systematization of violations according to nine parameters, creation of a database of violations (DB);
2- analysis of the database according to the "WHAT" parameter and identification of bottlenecks - events;
3- identifying the causes ("WHY" parameter) of all events from point 2 of this technique. Determination of the most important reasons (risks) and their acceptability;
4- multi-parametric analysis of the risk DB and identification of prerequisites for violations to prevent bottlenecks;
5- support for making management decisions.

### 2.1 Modeling the interaction of railway system components

The relationship between the principles of least action (Pr.5) and the bottleneck (Pr.6) can be described as a dichotomous (Pr.2) "consumer-satisfier" interaction, which makes it possible to use the well-known mathematical models of V.Volterra [7] and biotic models [8]. A set of interaction models of two components of the system is given in Table 1. These models are used to analyze and predict the state of the transport system.

In Table. 1, $N_1$ and $N_2$ mean the dimension (for example, the number of elements) of two sets.

| Type of interaction | Effect of components | | Mathematical model |
|---|---|---|---|
| | 2nd to 1st | 1st to 2nd | |
| *1. Competition:* mutually oppressive rivalry | – | – | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1 - \gamma_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \mu_2 N_2 - \gamma_2 N_1)\, N_2$ |
| *2. Amensalism:* one-sided oppressive rivalry | – | 0 | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1 - \gamma_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \mu_2 N_2)\, N_2$ |
| *3. Parasitism (predation):* "request - satisfaction" | – | + | $\frac{dN_1}{dt} = (\lambda_1 - \gamma_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (-\lambda_2 + \gamma_2 N_1)\, N_2$ |
| *4. Commensalism (freeloading):* one-sided positive competition | 0 | + | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_1 - \mu_2 N_2 + \gamma_2 N_1)\, N_2$ |
| *5. Neutralism:* Balance | 0 | 0 | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \mu_2 N_2)\, N_2$ |

| | | | |
|---|---|---|---|
| 6. *Amensalism:* one-sided oppressive rivalry | 0 | — | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_1 - \mu_2 N_2 - \gamma_2 N_1)\, N_2$ |
| 7. *Parasitism (predation):):* Batesian mimicry | + | — | $\frac{dN_1}{dt} = (-\lambda_1 + \mu_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \gamma_2 N_1)\, N_2$ |
| 8. *Commensalism (freeloading): one-sided positive competition* | + | 0 | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1 + \gamma_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \mu_2 N_2)\, N_2$ |
| 9. *Mutualism:* cooperative positive activity | + | + | $\frac{dN_1}{dt} = (\lambda_1 - \mu_1 N_1 + \gamma_1 N_2)\, N_1;$ <br> $\frac{dN_2}{dt} = (\lambda_2 - \mu_2 N_2 + \gamma_2 N_1)\, N_2$ |

Table 1: Types of models of joint interaction of two sets-components of a self-organizing system of transport system.

The peculiarities of the transition from one form to another are that the change of symbols "+" to "-" and vice versa can only go through "0", as shown in Fig. 4. This fact is emphasized by the arrows inside the table. 1.

Here, "+" means that an increase in the number of elements of one component leads to an increase in the number of elements of another type, "-" means that an increase in the number of one component leads to a decrease in the number of elements of the second, and "0" means no effect on the change in the number of elements between components.

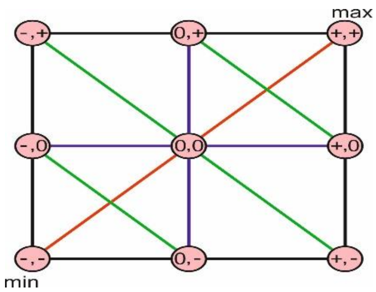


Figure 4: The sequence of the transition between interaction models in a dichotomous structure.

Depending on the modeling tasks, an appropriate modeling concept is developed.

## 3 Results

The paper presents a description of some sections of the unified theory of self-organizing systems. This is a proprietary development that can be applied to systems of various nature: technological, social, man-machine and others. The universality of the theory is explained by the fact that its creation is based on the analysis and generalization of many areas of knowledge in which the processes of self-organization and adaptation are studied: biology, physiology, ecology, cybernetics, systemology, synergetics, sociology, etc.

Practical application of the unified theory of self-organizing systems, dedicated to the most extensive aspects of the activity of transport systems: management, analysis of development and modeling to achieve the main goal of the system - to ensure a stable balance of activity in unity and interaction with the environment.

The main result of using a unified theory of self-organizing systems will be the effective operation of systems in conditions of risks and crises.

## 4 Conclusions and Contributions

The method of identifying a hidden statistical regularity (paragraph 2.1) and its use in solving the tasks of managing transport processes and structures confirmed the adequacy of the unified theory of self-organizing systems to the realities of the functioning of transport systems.

To model the development of a self-organizing system, a set of mathematical models of Volterra and biocenotic interactions is proposed. These models are universal in nature. This approach to modeling allows you to evaluate options for system reform and choose the most effective one. Taking into account the complexity of transport systems and their large size, the complex of interaction of two subsystems presented in Table.1 is the basic stage of designing a technique for solving the problem of restructuring assessment and the "paradox of development".

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