Development of the Theory of Organizational and Technological Reliability of Transport Systems Based on Intelligent Technologies

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Abstract. The necessity of developing the theory of organizational and technological reliability of transport systems based on intelligent technologies is substantiated: technical and technological safety, financial and production efficiency, quality of transport services are ensured. The necessary categorical research apparatus has been clarified and systematized (concepts: cognitive analysis of transport systems, organizational and technological reliability of transport systems, collective intelligence and fractal organization of the transport network); attention is focused on the main directions of this development. In particular, digital and intelligent technologies are introduced: translation of an expert specialist's natural intelligence to a machine, the synthesis of the collective intelligence of the network organization of work (on the example of the port station), the use of machine intelligence (neuro-fuzzy models); improvement of mathematical research tools (introduction of a configurable two-parameter beta distribution, fractal technologies of complex transport systems' organization and research).

Keywords: Transport systems, Organizational and technological reliability, Intelligent technologies, Collective intelligence of network organization of work, Fractals in transport.

1 Problem statement

The organizational and functional structure of transport systems (TS) management hinders the introduction of the process approach in transport, which is necessary for the formation of transport corridors connecting regional economic systems of different levels, for the implementation of end-to-end technologies, for example, door-to-door cargo delivery technology. A universal research tool well adapted to the description of transport processes is the theory of organizational and technological reliability (OTR) [1, 2, 3].

Briefly, the essence of OTR is as follows:

- As opposed to the technical and technological reliability of devices and systems, the concept of "organizational and technological reliability" is introduced, that is reliability that depends on the process organization, on the technology of its implementation, but not on properties of the objects composing the TS.

- OTR uses the network representation of TS, which allows to remove a number of system restrictions (strong dependence between network agents, rigid hierarchical scheme of links between them, functional and territorial principle of management) and thus to expand the range of studied TS with a simultaneous increase in their manageability as a whole.

- Together with the conventional for probabilistic systems normal distribution law of random events OTR actively uses the two-parameter beta distribution law, which better reflects the subjective vision of the transport problems of the manager and the expert and is more flexible in TS use (modeling and forecasting).

In this research the access to the artificial intelligence, as the necessary condition for the development of the TS consists of several aspects:

1. The translation of the natural intelligence of a specialist and developer into synthesized transport systems. Several aspects can be mentioned here:

- The cognitive analysis toolkit is proposed for TS the study [4], which consists in constructing cognitive maps linking causes and consequences, criteria and control effects, and reflecting the nature of human thinking and activity in the system.

- The use of a two-parameter beta distribution function, along with the traditional normal distribution, adjusted by a human, rather than formed only for reasons of the requirements of classical probability theory [5].

- Building fuzzy subjective models reflecting the uncertainty of the object under the study and the linguistic variables and fuzzy ways of thinking used by a human [6].

2. Formation of the collective intelligence of the network organization of the port station operation. In the studies of Bakalov M.V. [7] and Shapovalova Yu.V. [8], the ideas of the theory of active systems are adapted to transport problems. In particular, on this basis, they solve the problems of coordinating the conflicting interests of transport and logistics chains agents of the same and different levels of management. This toolkit is well suited to similar tasks for port TS agents. A reflection mechanism should be added to the development of the ideology of the theory of active systems, which allows when making conflict decisions to take into account the possibilities of the subject to proceed from the assumptions "I think that you think that I ...".

3. Use of machine intelligence (neuro-fuzzy models) for identifying complex dependencies, forecasting and decision-making mechanisms [9]. The cited work investigated vehicle monitoring and control systems using deep neural networks. However, this device has proven itself well both in the tasks of identifying unknown dependencies characterizing complex transport processes and in the tasks of managing them.

Another promising area of application of neuro-fuzzy models is seen in improving the road information and logistics system (RILS) [10]. In the existing ideology of RILS development, it is supposed to use machine intelligence in the form of neural network synthesis. If we proceed to the creation of neuro-fuzzy models, this will also allow us to take into account the experience of an expert specialist operating with linguistic variables and fuzzy concepts.

2 Systematization and refinement of the categorical apparatus of the study

Definition of OTR. Traditionally, the readiness coefficient of the research object is used as a measure of the OTR assessment [11]:

$$k = T/(T + \sum t_{oti}) \quad (1)$$

where T is the time of failure-free operation the object,

$t_{\text{от}i}$ is the failure time of the i-th element of the object.

The author [11], analyzing construction projects, adapts this notion to two particular aspects:

- timing of the project preparation;
- the cost of the project.

He gives the corresponding formulas adjusted according to (1). Thus, in general, a vector of similarly calculated indicators is obtained that characterize the OTR from different aspects (in a complex way).

Developing the theory of OTR Kvint M.Yu. introduces the concept of organizational and economic reliability (OER) as an integral part of OTR [12]. That is, determines the ability of the organizational and economic system to be resistant to external influences and internal violations in terms of maintaining organizational and economic security. As a numerical estimate of the OER, the author suggests using a measure of deviation Q_f of the actual data from the planned ones. Turning to dimensionless values, calculating the proportion of deviation in the planned indicator Q_p, we obtain a numerical, probabilistic-like measure of OTR:

$$k = (Q_p + Q_f)/Q_p \quad (2)$$

where Q is some economic indicator (costs, profitability, etc.). In this formulation, the sign *k* has an important semantic meaning.

The author [12] applied the developed OER model to the assessment of the quality of track maintenance works and the costs of their implementation that ensure the safe movement of trains.

The purpose of the research in [1] was to develop general theory of organizational and technological reliability of production processes in transport. This theory emerged at the interface of management and transport systems theory. It examines from a systemic perspective: organizational structures, hardware and software complexes of transport, and methods of organizing the effective functioning of industrial transport facilities. Applied aspects are considered on the example of railway transport. The present study (the first objective) is devoted to the specification and development of the main provisions of the OTR.

The essence of the cognitive approach consists in structuring the problem (helping an expert formalize a complex situation), developing the most effective management strategy based on intuition and on an ordered and verified knowledge of a complex system [4, 13].

Fractals. Fractals are a natural mechanism of the development of various objects of the world around us [14]. Fractals are hierarchical structures consisting of parts, each of which in some sense is similar to a more general (in hierarchy) component. Portside and transport systems in general are such. The main defining properties of fractals are:

- Irregularity not described by traditional mathematical constructions.
- The main function of fractal's shaping where self-similarity is manifested in the fact that the part has the same shape as the whole. That is, the part encodes the whole. This property is preserved during parallel transfers and zooming.
- The fractal dimension of the space under the study is greater than its topological dimension, therefore fractal spaces allow describing the tortuosity and irregularity of the boundary of the object under the study. The transition from topological to fractal space allows us to describe the gaps, gluing, which are so many in socio-economic, technical and technological systems.
- Fractal is generally defined recursively (by a formula or an algorithm).

The beta distribution is determined by the ratio [5]:

$$f(x, \alpha, \beta) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha,\beta)} \quad (3)$$

where $B(\alpha,\beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}$ and G is the Gamma function.

The beta distribution, as seen in (3), is similar to the binomial one, but simulates probability, whereas the binomial distribution models the number of events. Moreover, in OTR, we often deal with subjective probability (expert's assessment) and the beta distribution apparatus allows us to operate with this probability.

The probability density of the beta distribution can have a different shape: it can be *U*-shaped with asymptotic ends, bell-shaped, strictly increasing or decreasing, or even just a straight line segment.

The second objective of this study is to adapt the above tools to the problem formulated in the topic.

3 Cognitive analysis

The issues of cognitive modeling of transport systems are investigated in [13]. In particular, attention is focused on the role and place of "cognitive structuring", the stages of cognitive analysis, the building of cognitive maps, and the application of cognitive modeling in transport decision-making support systems.

Figure 1 proposes a simplified cognitive map (functional graph), revealing the role and place of port transport and technological systems (PTTS) in the development of the region, interstate relations (transport corridors) of the transport industry as a whole. In the full cognitive map, criteria indicators, influencing factors and their connections with the parameters of the process under study are indicated.

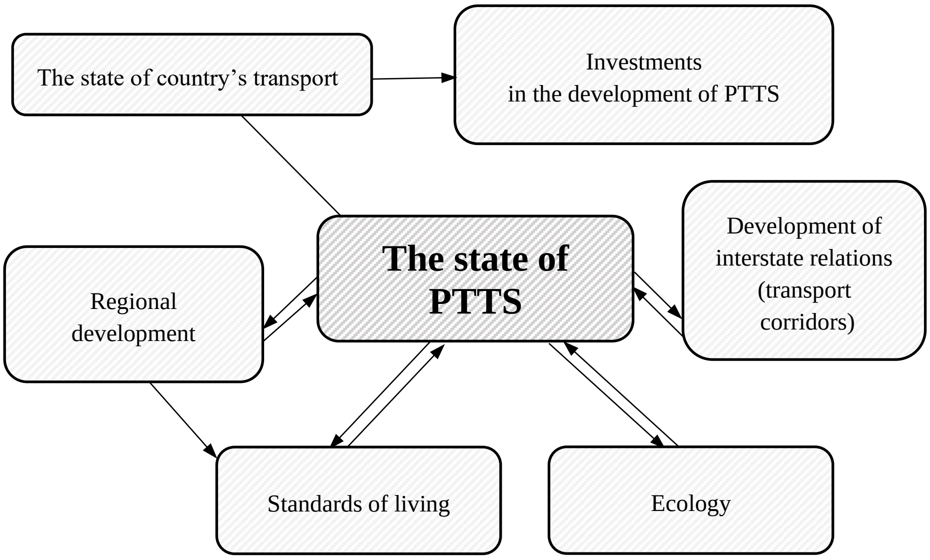

Fig. 1. Cognitive map of the role and place of port transport and technological systems (PTTS).

With the help of a special software system of cognitive modeling (SSCM), possible scenarios for the TS development can be simulated. The cognitive map makes it possible to identify the totality of positive and negative feedbacks in the system, and, consequently, to determine opportunities for stabilization and growth of transport processes indicators. In this case, natural intelligence manifests itself in the building of cognitive maps, assessing the sustainability and prospects of the development and degradation of the TS. Machine intelligence, using SSCM, takes on the problems of large data dimensionality, provides the necessary computing speed.

4 Beta distribution in the problem of port station management [14]

The introduction of a configurable two-parameter distribution significantly expands the possibilities of probabilistic approaches (compared to the normal distribution law). It allows us to extend and generalize the ideology of network analysis, which previously relied only on the normal and its derived distribution laws. Now the tasks of risk assessment, optimal distribution of tasks, evaluation of the duration of work, calculation of the critical path in the network, simulation modeling with various network parameters and structural features are more closely linked to the intuitive ideas of an expert.

The probability density of the beta distribution corresponds well to the normal distribution if $\alpha + \beta$ is large enough, and α and β are approximately the same.

It is also shown in [14] that if α <1, β<1, the probability density of the beta distribution takes a U-shape, *f*(*x*, 2, 2) will be ring–shaped, *f*(*x*, 1, 1) will be a uniform distribution.

To estimate the duration of work in the network, the preferred parameters of the beta distribution are $\alpha = 1$ и $\beta = 2$ [15]. The beta distribution in this case has the form:

$$P(t) = \frac{12(t-T_{min})(T_{max}-t)^2}{(T_{max}-T_{min})^4}. \quad (2)$$

In (4) the following is indicated: T_{min} as the minimum time required to perform these works; T_{max} as the maximum time required to perform these works under the most unfavorable circumstances. T_{min} is calculated according to the critical path of the network graph.

5 OTR of the transport process [15]

The uncertainties and randomness of the operation of complex transport facilities require the use of probabilistic characteristics of network graph estimates. These include:

– T_{exp} as the average value of the random variable “expected time of work completion”;

– σ^2 as variance (a measure of uncertainty) of the random variable "expected time of work completion".

If we assume that "expected time of work completion" has the beta distribution then T_{exp} is calculated by two values (T_{min}, T_{max}) by the formula:

$$T_{exp} = (3T_{min} + 2T_{max})/5. \quad (5)$$

In this case the variance σ^2 is calculated by the ratio:

$$\sigma^2 = [\frac{T_{max}-T_{min}}{5}]^2. \quad (6)$$

With T_{exp} values for each individual work of the network schedule it is possible:

- to calculate early and late completion deadlines for the entire schedule;
- duration of the critical path;
- time reserves, general for the entire schedule and private for its individual components.

In a probabilistic network model, the variance of the critical path duration is determined by summing the variances of the sequences of activities included in this path.

The probability of work completion in the network model within the specified time (reliability of the network model) under the assumption of a normal distribution can be determined by the formula:

$$p(T_{exp} \leq T_d) = \Phi\left(\frac{T_d-T_{exp}}{(\sum \sigma^2)^{0,5}}\right) = \Phi(\mathrm{a}). \quad (7)$$

In (7) it is indicated: p as the probability of work completion within the specified time; T_d as the planned (directive) deadline for the work completion; T_{exp} as the expected deadline for work completion taking into account possible violations of the technological process; $\Phi(\alpha)$ as the value of the Laplace function.

The experience of network planning and management allows us to give specific recommendations on the classification of numerical values of risk p:

- If $p < 0.35$, then the probability of work completion within the planned period is unacceptably low. It is necessary to return to the procedure of network graph synthesis and optimization.

- If $p > 0.65$, then the planned work will be completed on time with a high probability. At the same time, this means that an excessive amount of resources is included in the schedule, which reduces its cost-effectiveness. It can be optimized.

- If $0.35 < p < 0.65$, then the constructed network schedule of works is accepted for execution without changes.

6 Fractals [16-19]

In theory [16] "pure" fractals are considered that are not burdened with restrictions. As a result, symmetrical, infinitely divisible fractals are obtained which cannot be observed in practice. All kinds of constraints (spatial, temporal, resource) deform fractals creating unique structures. To research them it is important to define clearly the conditions of their origin and development.

The theory of fractals is shifted to socio-economic objects in several aspects:

a) The occurrence of fractal structures in production and business processes [17]. Indeed regardless of its scale the organization production business process develops according to the following algorithm: an innovative business idea is generated; financial, personnel, intellectual, organizational and other types of investments of the project are made; scientific study of the project is carried out (scientific research work, research and development project, experimental sample, pilot operation, production is being established; the product and/or service production; access to the relevant market (organization of advertising, marketing promotion of the product, sales chain organization, production distribution). These iterations take place at small enterprises, their various associations, in the region, industry and state economy. This similarity creates fractal structures of production and business.

b) Fractals are a basic property of a self-organizing organism, which can also be technical, technological and socio-economic systems [18]. In this study, an "organism" is understood as a self-organizing system characterized by many needs that can be grouped into five main groups: energy, transport, environmental, technological and informational. These groups are called clusters. In turn, each of these five clusters distributes its resources to the similar five subclusters. For example: a transport cluster needs energy support, transport (self-sufficiency), ensures environmental sustainability, develops technologies, information systems, etc. This process can be extended to the next level. That is, a hierarchical self–similar structure of resource allocation - a fractal - has emerged.

Volov V.T. singles out a maximum of 3-4 levels of hierarchy [18]. In this case the minimum size of a self-organizing organism, the resources available for its development and the immersion space are the limitations.

The number of clusters allocated is debatable issue in this formulation. Different areas of research, as well as different requirements for the model accuracy may require a different distribution of needs across clusters of objects under the study.

c) Territorial fractals [19, 20] arising in physical space.

In the study [19], the fractal method is used to detect group objects of transport infrastructure in aerospace images. That is, the recognizable images are not images traditional for the recognition theory [6] (geometric figures of Euclidean geometry), but fractals. This increases the adequacy and accuracy of recognition.

Similarly, in [20] fractals are used as a tool for territorial planning of agglomeration systems. Separate parts of the urban agglomeration (industrial zones, "sleeping areas", recreation areas, transport communication, etc.) interact with each other. There is an iterative process in their development: for example, the creation of industry requires housing, social infrastructure, transport. Similar transformations occur within each iteration. Therefore, fractals are one of the models for creating agglomeration systems. At the same time, both positive and negative synergistic effects arise. The task is to maximize the former and minimize the latter. Similar studies should be carried out to assess the development of transport systems.

7 An example of the formation of an information and management fractal in transport

Let us consider the classification of existing and developing information and management systems serving the transport industry (table 1).

Table 1. Classification of technological processes on the railway network [10].

Type of the process		Coverage area
UNTP	Unified network technological process	Railway network of JSC “Russian railways”
UTPP	Unified technological process of the polygon	Enlarged railway polygon
UITP	Unified integrated technological process	PTTS, railway junction
UTP	Unified technological process	Non-public stations and tracks
TP	Technological process	Railway station

Currently, they are developed and implemented in transport with various degrees of functional completeness, information security, intelligence, and demand for

[1] Borrowed in [10].

practice [21-23]. However, it is obvious that all these processes are similar in organization, functions, composition of tools and are embedded in each other. Technically, they are based on the digital and intellectual transformation of the transport industry. That is, the main features of fractal organization are fulfilled. These are iteration (five levels) and self-similarity.

It is possible to describe this fractal structure both within the framework of approach a) and within the framework of approach b). In the first case, we will confom a universal procedure for the implementation of transport production and business processes at all levels, in the second we will investigate their resource components (financial, labour, information, material).

Thus, the OTR toolkit is completed by the mechanism of fractal (natural) modelling and development of complex objects in transport.

8 Conclusion

1. It has been shown that the theory of organizational and technological reliability is a universal research tool well adapted to the process organization of transport production.

2. The essence of transport organizational and technological reliability theory has been revealed and the ways of its development have been determined: intellectualization, cognitive analysis, modelling of random dependencies using beta distribution, fractal analysis of processes and structures in transport.

3. The role of artificial intelligence in the development of organizational and technological reliability has been defined: the translation of the natural intelligence of a specialist and developer into synthesized transport systems; the formation of collective intelligence of the transport network organization; the use of machine intelligence (neuro-fuzzy models) to identify complex dependencies, forecasting and decision-making mechanisms.

4. The categorical apparatus of the study of organizational and technological reliability in transport has been systematized and specified.

References

1. Vereskun V.: Organizational and technological reliability and operational efficiency of production facilities of railway transport. Publishing House of Siberian Transport University, 256 p. (2010).
2. Kozyr G.: Introduction of process approach in management activities. Automation and telemechanics on railway transport: A collection of reports of the Ninth International Scientific and Practical Conference "Transzhat - 2018", pp. 85–96 (2018).
3. Shalyagin G., Potapova I.: Organizational and technological reliability: a methodological guide for practical training. Publishing House of Far Eastern State Transport University, 52 p. (2006).
4. Gorelova G., Lyabakh N.: Cognitive analysis: problems of application and development. New Technologies 4, pp. 16–21 (2016).

5. Beta distribution: intuition, examples, and derivation // https://medium.com/nuances-of-programming /beta-distribution-intuition-examples-derivation-B4-4662b929305e1, last accessed 2023/03/10.
6. Adadurov S., Gapanovich V., Lyabakh N., Shabelnikov A.: Railway transport: on the way to intelligent management: monograph. SSC RAS, 322 p. (2010).
7. Bakalov M., Zubkov V., Chernyaev A.: Methodological basis and mechanisms of development of transport polygons: manual, 78 p. (2017).
8. Shapovalova, Yu.: Methods of research of complex transport facilities Proceedings of the Rostov State Transport University, 2, pp. 84–89 (2017).
9. Amosov O., Amosova S., Ivanov Yu., Zhiganov S.: Modeling of an intelligent system of management and access control of vehicles using deep neural networks. Information technologies, 25 (2), vol. 25, pp. 116–127 (2018).
10. Chebotareva E.A. Theory and methodology of transport production organization in port transport and technological systems: monograph, 267 p. (2020).
11. Shprits M.: Operational assessment of organizational and technological reliability of construction objects. International Scientific Research Journal, 4 (58), pp. 126–128.
12. Kvint M.: Assessment of organizational and economic reliability of track works on railway transport. Scientific problems of transport in Siberia and the Far East, 2, pp. 44–47 (2009).
13. Rosenberg I.: Cognitive management of transport. Economic Consultant, 2, pp. 47–52 (2015).
14. Beta distribution: intuition, examples, and derivation // https://medium.com/nuances-of-programming /beta-distribution-intuition-examples-derivation-B4-4662b929305e, last accessed 2023/03/10.
15. Vereskun V., Shepilova E.: Mathematical tools for network technological process management. Transport: science, technology, management, 8, pp. 12–13 (2013).
16. Latypova N.: Fractal analysis: textbook. Publishing Center "Udmurt University", 120 p. (2020).
17. Shenyagin V., Yurkov V.: Continuous interest accrual as a large-scale symmetry of financial and economic process and fractality property. Economic Journal, 3. (2008).
18. Volov V.: Fractal-cluster approach to the description of the fundamental regularities of biological organisms development. Proceedings of the Samara Scientific Center of the Russian Academy of Sciences, 5(2), vol. 20, pp. 204 – 213 (2018).
19. Markov E., Andrusenko A., Shabakov E.: Fractal method for detecting group objects of transport infrastructure in images. Intellectual Technologies on Transport, 4, pp.10–15 (2016).
20. Pavlov Yu.: Fractals as a tool for territorial planning of agglomeration systems. Fundamental research, 10, pp. 2242–2248 (2013).
21. Zubkov V., Ryazanova E., Anoshkin K.: Proposals for the Development of the Road Information Logistics System (RILS). Proceedings - 2022. International Russian Automation Conference. RusAutoCon, pp. 527 – 536 (2022).
22. Zubkov V., Musienko N., Anoshkin K.: The Prospective Model of Organization of Freight Transportation on the North Caucasian Railway Range. Lecture Notes in Networks and Systems. International School on Neural Networks, vol. 510, pp. 543–554 (2023).
23. Zubkov V., Musienko N., Ryazanova E.: The Analysis of the Cargo Base and Development of Measures to Increase the Competitiveness of Freight Railway Transportation. Lecture Notes in Networks and Systems. International School on Neural Networks, vol. 509, pp. 1–11 (2023).