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Fuzzy Systems for Analysis of Technical and Economic Resilience

Kozlovsky A.N.[1] Nedosekin A.O.[2,*] Abdoulaeva Z.I.[3] Reyshakhrit E.I.[4]

[1]*Northwest Open Technical University, Russian Federation*
[2]*LLC «C-FINANCE», International Academy of Ecology, Human Security and Nature Sciences (IAELPS), Russian Federation*
[3]*Peter the Great St.Petersburg Polytechnic University (SPbPU), Russian Federation*
[4]*Saint-Petersburg Mining University, Russian Federation*
[*]*Corresponding author. Email: sedok@mail.ru*

ABSTRACT
The article proposes a fuzzy-logical approach for analysing the resilience of technical and economic systems in scope of unified framework. Of the richest arsenal of fuzzy models and methods in the work, linguistic Zadeh variables, fuzzy numbers, matrix aggregate calculator (MAC), and a 4x6 matrix are briefly described. The integrated efficiency of a system is presented as a fuzzy random variable of an arbitrary form. On this basis, it is possible to assess the risks and chances of a system, as well as the level of its resilience on the basis of an integral assessment by the MAC method. The central problem in the analysis of technical systems resilience is the high computational complexity. In economic applications, the big-gest problem is the lack of quality input. Applied fuzzy-cybernetic system analysis methodology allows to study complex systems consisting of subsystems of various nature on a unified methodological basis, using the same modelling tools
Keywords: *global resilience, linguistic variables, fuzzy numbers, balanced scorecard (BSC), risk, chance, matrix aggregate calculator (MAC), 4x6 matrix*

1. INTRODUCTION

The paradigm of sustainable development of complex systems implies that such systems should maintain their effectiveness (in whole or in part) in the face of environmental challenges, both negative and positive content, and also have the property of rapid recoverability - returning system efficiency to a nominal level after large-scale impacts.

In the twentieth century, studies of the resilience of both technical and economic systems were carried out, while technical systems were studied in the survivability paradigm, and economic systems mainly in the financial stability paradigm. From the standpoint of the scientific achievements of this century, the approaches of the last century show their insufficiency and need to be developed. Two new paradigms can help with this: the vitality paradigm [1], which endows all systems with a special viability property, and the global resilience paradigm, which considers the stability of complex combined technical, economic and organizational systems when separate subsystems are part of the «system-of-systems» that interact with each other according to certain rules.

The viability of systems of any type stems from the fact that they do not act on their own, but under the control of their over-systems, which are composed of individuals and human collectives. All systems, regardless of their nature, are appropriate to consider from a cybernetic standpoint,

highlighting their common properties; a) subjectivity; b) viability; c) openness to the outside world (susceptibility to challenges); d) manageability; e) observability; e) homeostasis with the environment; g) action under conditions of restrictions; h) the coverage of the system with positive and negative feedbacks. The concept of a cybernetic system predetermines that the functioning of systems is carried out under conditions of significant information uncertainty, both in terms of the manifestations of the external environment and in terms of the reaction of the system to these manifestations. This, in turn, places certain demands on resilience models. In particular, if the requirement of mass character and homogeneity of statistical evidence is not fulfilled, then probabilistic models cannot be applied without significant reservations. Global resilience is defined in [2]: «Resilience is an emergent property associated with an organization's capacity to continue its mission despite disruption through mindfulness [3], resourceful agility, elastic infrastructures and recoverability, e.g. [4, 5]. Therefore, resilience is a combination of technical design features, such as fault-tolerance and dependability [6], with organizational features such as mindfulness, training and decentralized decision making [3, 7]».

This, in particular, presupposes the inclusion of technical and economic systems in the composition of their managing organizational over-systems. In this case, the economic and technical systems become private subsystems, and the assessment of their resilience, regardless of the consideration of the organizational super-system, has a sketchy, private character. For the resilience assessment to be complete and consistent, it is necessary to specifically model the organizational component of a complex system. For example, in the theory of dependability, the factor of recovery intensity is well known, which is completely determined by the efficiency of the repair device attached to the technical system. Similarly, the speed of reconfiguration of the system is directly related to the trained personnel of the system to act in extreme circumstances, to make optimal decisions in a limited time reserve.

In the sources devoted to resilience analysis, systems for various purposes are considered separately. For example, a detailed review of publications on the resilience of technical and infrastructure systems is presented in [8]. A review of the work on the analysis of the resilience of economic systems is done in [9]. The purpose of this work is to propose a framework that would allow us to analyse technical, economic and organizational systems together, in the course of their interaction, as part of a unified approach to modelling, briefly highlighting our own developments in this direction.

The mathematical tools used for resilience analysis are also wide and highly de-pendent on the specifics of the system to be modelled. When modelling, scenario approaches, approaches based on Bayesian networks (for example, [10]), as well as traditional analytical relations connecting parameters within the resilience model are used. To a lesser extent, fuzzy-logical methods of resilience analysis are presented. At the same time, decision making under uncertainty is best modelled on the basis of fuzzy systems. In this paper, we consider the main fuzzy models and methods that can be used in the analysis of the resilience of systems of various natures.

2. METHODS

Management begins with observation. Recognition of an event as happening is based on an analysis of quantitative parameters. In the simplest case, when the observed parameter goes beyond its agreed normative values, the organizational over-system diagnoses negative if the parameter “goes south” or positive if the parameter “goes north”. In both cases, a partial (local) resilience violation is diagnosed, which should be analysed and compensated by the control system. In particular, the failure of one of the elements of the technical system leads to a partial or complete decrease in the efficiency of the system. This reduction is compensated automatically during recon-figuration of the system if the failed element was backed up, or by manual recovery, with the replacement of the failed element for an indefinite time if there is no redundancy. Failure causes a loss of system resilience, its localization and recovery from failure return resilience to the system.

Accordingly, modelling the resilience of a system begins with modelling the effectiveness of its functioning. The simplest model of system efficiency is a binary structural-logical model, when the system performance is described by a bipolar graph. In this case, the efficiency of the system is either equal to 1 if the graph maintains connectivity between the two poles of the graph, or equal to 0 if the connectivity is lost due to failures of elements (single or group). Binary performance models are actively used in reliability and survivability analysis, which, in our opinion, are special cases of global resilience of technical systems [11]. At the same time, they reveal their complete failure when it is necessary to model the resilience of economic systems.

To overcome discreteness in the description of the state space of a technical sys-tem, they resort to a description of the operation of systems in terms of functional models. Such models are especially common in electric power applications. In economics, models of this class are balanced scorecards (BSC) [12]. The advantage of models of this class is the exact reproduction of the system’s functionality; the dis-advantage is the unaccountability of many states, which does not allow the use of traditional logical analysis methods in the analysis. The transition from a continuous state space to a discrete one can be carried out by aggregating states, for example, on the basis of normalizing the level of efficiency of the functioning of the system as a whole and individual subsystems in its composition.

Normalization of factor levels can be carried out using the Zadeh linguistic variable [13], when the spectrum of quantitative levels of factor corresponds to term-set of linguistic values expressing an expert assessment of the parameter level. This is the simplest case to identify the work of one of the elements of the system in qualitative terms, reducing the space of states of an element to a finite set of qualitative gradations of the effectiveness of its functioning. If in an elementary binary model an element has only two states - operability or failure, then in the model of qualitative gradations of such states there may already be five: a very low level of efficiency, a low level, an average level, a high level and a very high level. Such high-quality logic allows us to successfully model the development of gradual failures in a system, when a separate element of the system itself is a subsystem and loses its efficiency not stepwise, but gradually, as the subsystem's resource potential is exhausted.

In economic applications, all key performance indicators of an organization may be subject to quality gradation. This, in turn, allows establishing fuzzy-logical relationships between the factors of the model, according to the IF-THEN principle. Such connections, implemented within the framework of BSC, allow using BSC as a hybrid fuzzy system, where traditional calculations are combined with fuzzy-logical inference.

In the course of resilience analysis, it is necessary to model not only the state space of a complex system, but also the state space of the external environment surrounding the system. For example, in the early models of technical survivability, in the interests of military applications, the damaging effects caused by the spatially distributed system were interpreted as probable impact hypotheses, while the application of the impact to the element did not necessarily end with its defeat the first time (the phenomenon of an element's resistance was simulated). Similarly, in economic applications, the negative impact of a contracting market on sales results is modelled. In both cases, the impact is considered as a signal applied to the exogenous "inputs" of the cybernetic system model. Since such a signal itself has vague parameters (due to the limited predictive ability of experts), the cybernetic "output" of the system is a fuzzy random variable in the sense of Puri-Ralescu [14], which is axiomatically defined in two mathematical spaces simultaneously - probabilistic and possibilistic. Such a cybernetic "output" in a technical system is its technical efficiency (for example, the power of an autonomous cold supply system). In the economic system, such an "output" may be return on equity (ROE), return on invested capital (ROI), or internal rate of return of a project (IRR).

A double convolution of the integral indicator of the system's efficiency (in probabilistic and in possibilistic spaces) allows us to make a risk assessment that the efficiency indicator will go down below the standard level based on the results of negative impact:

$$\text{Risk} = \text{Poss}\ \{\text{Eff} < \text{Eff1} \mid \text{AE}\} \qquad (1)$$

Here "Poss" is the mathematical sign of the possibility, Eff is the efficiency of the system is a fuzzy random variable, Eff1 is the lower efficiency standard characterizing the boundary between acceptable and unacceptable levels of the system's functioning, "|" is the "in case of" sign, AE (Adverse Effect) is a set of adverse effect parameters.

In a similar way, one can assess the chance that the system will go beyond the normatively expected level of its effectiveness according to the results of favourable environmental impact (for example, unpacking new markets):

$$\text{Chance} = \text{Poss}\ \{\text{Eff} > \text{Eff2} \mid \text{CE}\} \qquad (2)$$

Here Eff2 is the upper efficiency standard characterizing the boundary between acceptable and extraordinary levels of system functioning, CE (Challenge Effect) is a set of parameters of the environmental stimulus to the system.

Thus, three signals can simultaneously arrive at the input of the organizational control over-system - efficiency, risk, and chance (see Fig. 1). In this 4x6 matrix, these are four strategic perspectives (A - Assets, P - Processes, R - Relationships, E - Effects), and the columns are six strategic maps (Threats, Opportunities, BSC, Risks, Chances, Decisions). Fig. 1 corresponds to the model of the economic system; if the BSC card is replaced in it by a functional model of the technical system, then the updated model is suitable for analysis of already technical resilience. Similarly, if we replace the BSC with a system of interconnected maps of individual subsystems as part of a complex technical-economic-organizational system, we can evaluate the level of global resilience for system of systems. At the same time, various types of external influences will be applied to various types of subsystems, and global resilience management decisions must be taken in a complex, based on the whole "bouquet" of influences on a complex system as a whole.

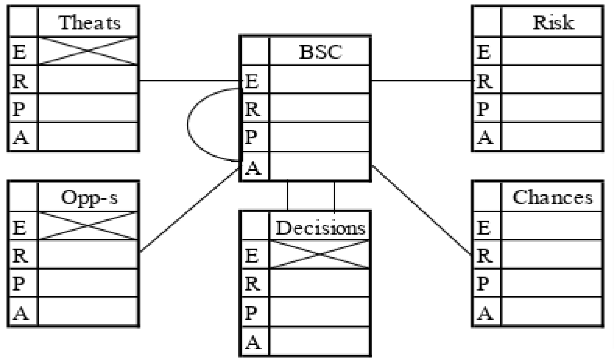

Figure 1. 4x6 matrix. Sources: [15,16]

3. RESULTS

After all the parameters of the system according to the results of external influence are determined in turn, we can begin to design response solutions aimed at increasing the resilience of the system. When designing solutions, you can use the method of matrix aggregate calculator (MAC, [17]), which can appear in both one-level and multi-level versions, depending on the complexity of the model used to analyse and design solutions.

In the simplest case, MAC is a matrix whose lines are three indicators: average expected efficiency, risk and chance. The current levels of these indicators receive their qualitative gradation in the MAC (they are fuzzyficated), and then a two-dimensional convolution of the obtained data is carried out with two weight systems: a) the weights of the factors themselves, which correspond to their significance for the integral assessment; b) weights corresponding to the system of linguistic gradations. At the output, we have an integral level of system resilience, measured from zero to one. The lower the level of resilience, the more radically applied solutions should be. For example, recognition of an organization as unprofitable at the moment (ROE<0) indicates a significant violation of the level of resilience and requires the initiation of decisions on crisis management, including painful measures to reduce costs and dis-miss excess staff.

Note: MAC technology is also successfully applied in BSC as modelling many-to-one relationships.

The task of ensuring the resilience of the system is to maintain conditionally constant level of a proportion between the resources mobilized by the system and the output results that the system generates from the results of the mentioned mobilization. If the optimal proportion shifts in one direction or another, the decisions should act in the opposite direction, i.e. have a stabilizing character. There are also states of "negative stability", when the system must be forcibly transferred to a qualitatively new state, even at the cost of a temporary loss of stability. A typical example of the above is the implementation of large-scale organizational changes in a stagnant company.

Often solutions to improve resilience acquire the properties of a technical or economic project. Modelling solutions in such a package is carried out according to the same rules as modelling manifestations of the external environment, only this time the impact is exerted by the controlling over-system. Decisions are applied to the exogenous parameters of the model of the controlled system, and then the control action propagates through the system, causing a counter-fuzzy response in the system. Thus, environmental challenges and signals from the controlling over-system begin to compete with each other; in dynamics, this causes a "racing effect": whose horse runs faster, this will be the combined result.

4. DISCUSSIONS

The tasks of resilience analysis are traditionally distinguished by high computational complexity. This is especially acute in technical applications, when the system contains several hundred exposed elements. In the course of solving the analysis problem, it is assumed that functionally operable states of the system are separated from the full set of states, which by default poses the problem of a complete enumeration of the states of the system and the exponential complexity of such enumeration. In [11], a number of methods are proposed for an approximate assessment of technical survivability, by replacing the initial logical circuit of the system's operability with a combination of series-parallel structures, the elements of which also are series-parallel structures with a reduced dimension (the fractal principle of regularization of systems with a complex structure).

Similarly, the high computational complexity of the polynomial class accompanies the modelling of the space of adverse effects on the system. Here, simplification is possible if we construct a two-sided estimate of the probabilistic distribution of actions over the elements of the system, replacing the inhomogeneous probability distribution with a homogeneous one. A number of such exotic distributions (including those that do not have a detailed analytical record) are also presented in [11].

Modelling the resilience of economic (and financial [18]) systems is free from the "curse of dimensionality" (the system does not contain discrete elements). But there arises the problem of purely unreliability of the source data; statistics in the traditional sense in economic applications simply does not exist. Accordingly, one has to make special model assumptions and filter the input data stream in order to achieve statistical data homogeneity, even in the first approximation.

5. CONCLUSION

The unified fuzzy-cybernetic methodology of system-of-systems analysis allows to explore complex systems consisting of subsystems of various nature on a single methodological basis, using the same modelling tools. Any real complex system is simultaneously inherent in technical, economic and organizational aspects. Some-times specific aspects are added to them (for example, military). But no complication of the system description can and should not lead to a change in the selected fuzzy-cybernetic modelling paradigm.

REFERENCES

[1] A.O. Nedosekin, The «vitality» feature as it presents in technical, economic and social systems: http://an.ifel.ru/docs/Vitality_110416.pdf (Russian edition), last accessed 2020/01/20

[2] G. Muller, T. Koslowski, R. Accorsi, Resilience – a New Research Field in Business In-formation Systems? In: Abramowicz, W. (eds) Business Information Systems Workshops. BIS 2013. Lecture Notes in Business Information Processing, vol. 160. Springer, Berlin, Heidelberg, 2013, pp 3-14. DOI: https://doi.org/10.1007/978-3-642-41687-3_2

[3] K.E. Weick, K.M. Sutcliffe, Managing the unexpected: Resilient performance in an Age of Uncertainty. 2nd edn. Jossey-Bass, San Francisco, US, 2007, 224 p. ISBN-13: 978-1118862414.

[4] CERT® Resilience Management Model, version 1.0, 2010, 78 p.https://resources.sei.cmu.edu/asset_files/TechnicalReport/2010_005_001_15230.pdf , last accessed 2020/01/20

[5] E. Hollnagel, D.D. Woods, N. Leveson, Resilience engineering: Concepts and precepts. Crc Press, Florida, US, 2006, 393 p. ISBN-10: 0 7546 4641 6

[6] Avizienis, A., Laprie, J.-C., Randell, B., Landwehr, C.: Basic concepts and taxonomy of dependable and secure computing. IEEE Transactions on Dependable and Secure Computing 1(1), 11–33 (2004). DOI: https://doi.org/10.1109/TDSC.2004.2

[7] P. Antunes, H. Mourão, Resilient Business Process Management: Framework and services. Expert Systems with Applications 38(2), 1241-1254 (2011) DOI: https://doi.org/10.1007/978-3-642-41638-5_1

[8] S. Hosseini, K. Barker, J.E. Ramirez-Marquez, A review of definitions and measures of sys-tem resilience. Reliability Engineering & System Safety, 145, 47- 61 (2016). DOI: https://doi.org/10.1016/j.ress.2015.08.006

[9] M. Buheji, Understanding the power of resilience economy: an inter-disciplinary perspective to change the world attitude to socio-economic crisis. AuthorHouse UK, 2018, 386 p. ISBN-13: 978-1546286677

[10] S. Hosseini, K. Barker, Modeling infrastructure resilience using Bayesian networks: A case study of inland waterway ports. Computers & Industrial Engineering, 93, 252-256 (2016). DOI: https://doi.org/10.1007/s11518-019-5440-x

[11] A.O. Nedosekin, V.V. Vinogradov, Z.I. Abdoulaeva, Functional survivability models and methods for tech systems with complex structure. Polytechnic University Publishing, Saint-Petersburg, 2018, 128 p. ISBN-13: 978-5-7422-6325-8

[12] P. Niven, Balanced scorecard evolution: a dynamic approach to strategy execution. Wiley, NY, US, 2014, 371 p. ISBN-13: 978-1-118-93901-7

[13] L. Zadeh, J. Kasprzyk,: Fuzzy logic for the management of uncertainty. Wiley, NY, US, 1992, 676 p. ISBN-13: 978-0471547990

[14] M.L. Puri, D.A. Ralesku,: Fuzzy random variables. Journal of Mathematical Analysis and Applications 114, 1986, pp. 409-422, URL: https://www.researchgate.net/publication/313167440_Fuzzy_random_variables , last accessed 2020/01/20

[15] A.O. Nedosekin, E.I. Reishahrit, A.N. Kozlovsky, Strategic approach to assessing economic sustainability objects of mineral sector of Russia. Zapiski Gornogo Instituta 237, 354-360 (2019). DOI: https://doi.org/10.31897/PMI.2019.3.354

[16] V.V. Vinogradov, Z.I. Abdoulaeva, Fuzzy-set economic stability analysis model of mineral complex of the Russian Federation. In: Shaposhnikov, S. (ed) Proceedings of the 19th Inter-national Conference on Soft Computing and Measurements, SCM 2016, pp. 489-490. IEEE, Saint-Petersburg, Russia (2016) DOI: https://doi.org/10.1109/SCM.2016.7519822

[17] Z.I. Abdoulaeva, D.F Kurbanbaeva, M.E. Topuzov, Application of the matrix aggregate calculator (MAC) for forecasting disease recommendation. In: Shaposhnikov, S. (eds) Proceedings of International Conference on Soft Computing and Measurements, SCM 2017, pp. 684-685. IEEE, Saint-Petersburg, Russia (2016). DOI: https://doi.org/10.1109/SCM.2017.7970689

[18] O.A. Pogrebova, E.A. Konnikov, D.F. Kurbanbaeva, Model assessing the sustainability of industrial enterprise development based on real option dynamic management model of innovations generations. Proceedings of 2017 20th IEEE International Conference on Soft Computing and Measurements, SCM 2017, 7970749, pp. 868-870. DOI: https://doi.org/10.1109/SCM.2017.7970749