NEURO-FUZZY METHOD FOR PREDICTING AND ASSESSING THE LEVEL OF TECHNOLOGICAL HAZARD IN CYBER-PHYSICAL CIVIL PROTECTION SYSTEMS

Vladyslav Yevsieiev
Kharkiv National University of Radio Electronics
Ukraine, 61166, Kharkiv, Nauky Ave., 14
E-mail:vladyslav.yevsieiev@nure.ua

Annotation: The paper proposes a neuro-fuzzy method for predicting and assessing technological hazard levels in cyber-physical civil protection systems, combining fuzzy inference with adaptive neural-network learning for processing heterogeneous sensor data and forming an integrated risk index. The proposed approach enables assessment of the current hazard level and prediction of its dynamics over a specified time horizon, supporting the transition from reactive monitoring to proactive detection of pre-accident and hazardous states. The feedback loop provides adaptive refinement of the neuro-fuzzy model using new data, which increases its applicability to various critical and industrial infrastructure facilities and supports informed decision-making in civil protection systems.

Key words: neuro-fuzzy method; cyber-physical system; civil protection; technological hazard; risk prediction; fuzzy logic; neural network; decision support

НЕЙРО-НЕЧІТКИЙ МЕТОД ПРОГНОЗУВАННЯ ТА ОЦІНЮВАННЯ РІВНЯ ТЕХНОГЕННОЇ НЕБЕЗПЕКИ В КІБЕРФІЗИЧНИХ СИСТЕМАХ ЦИВІЛЬНОГО ЗАХИСТУ

В. В. Євсєєв
Харківський національний університет радіоелектроніки
Україна, 61166, Харків, пр. Науки, 14
E-mail:vladyslav.yevsieiev@nure.ua

Анотація: У роботі запропоновано нейро-нечіткий метод прогнозування та оцінювання рівня техногенної небезпеки в кіберфізичних системах цивільного захисту, який поєднує нечіткий логічний висновок з адаптивним нейромережевим навчанням для опрацювання різнорідних сенсорних даних і формування інтегрального індексу ризику. Запропонований підхід забезпечує оцінювання поточного рівня техногенної небезпеки та прогнозування його динаміки на заданому часовому горизонті, створюючи передумови для переходу від реактивного моніторингу до проактивного виявлення передаварійних і небезпечних станів. Контур зворотного зв’язку забезпечує адаптивне уточнення нейро-нечіткої моделі на основі нових даних, що розширює можливості її застосування для об’єктів критичної та промислової інфраструктури й підтримки обґрунтованого прийняття рішень у системах цивільного захисту.

Ключові слова: нейро-нечіткий метод; кіберфізична система; цивільний захист; техногенна небезпека; прогнозування ризиків; нечітка логіка; нейронна мережа; підтримка прийняття рішень.

The relevance of the research is determined by the need to improve the accuracy and timeliness of predicting technological hazards in cyber-physical civil protection systems under conditions of uncertainty, dynamically changing hazard parameters, and heterogeneous data received from sensor systems. The application of a neuro-fuzzy approach makes it possible to combine the adaptive learning capabilities of neural networks with the ability of fuzzy logic to process incomplete and uncertain information, thereby creating the prerequisites for timely prediction of hazardous situation development and reliable assessment of technological risk levels. The development of such a method

will contribute to improving the effectiveness of intelligent monitoring and decision-support systems in the field of civil protection.

The idea of using a neuro-fuzzy method for predicting and assessing the level of technological hazard is to create an intelligent mechanism for continuous analysis of the state of a potentially hazardous facility based on data received from the sensor layer of a cyber-physical civil protection system. The proposed approach involves the integrated use of temperature, hazardous gas concentration, smoke level, pressure, vibration, and other monitored parameters of the technological environment. The acquired data are preliminarily normalized, filtered, and analyzed to detect deviations from the permissible operating conditions of the facility. The fuzzy component of the method transforms numerical parameters into linguistic assessments and makes it possible to account for the uncertainty, incompleteness, and inconsistency of sensor information. For this purpose, membership functions and a fuzzy rule base are formed to establish relationships between the monitored parameters and the current level of technological hazard. The neural network component provides adaptive adjustment of the fuzzy system parameters according to accumulated data on normal, pre-emergency, and emergency operating conditions of the facility. The integration of these components makes it possible to form an integral technological hazard indicator normalized, for example, within the range from 0 to 1. The value of this indicator can be used to determine the current state of the facility according to normal, warning, hazardous, and critical levels. At the same time, the method is intended not only to assess the current hazard but also to predict its changes over a specified time horizon while taking into account the dynamics of sensor parameters. This makes it possible to identify trends indicating that the system is approaching a critical state even before the established threshold values are actually exceeded. The prediction results can be transmitted to the upper level of the cyber-physical system to generate warnings and support decision-making by the responsible civil protection units. The main research hypothesis is that the combined application of the adaptive capabilities of neural networks and the fuzzy inference mechanism will provide a more reliable assessment of technological hazards compared with the use of static threshold criteria. It is assumed that the neuro-fuzzy model will be able to adapt to changes in the operating modes of the monitored facility and account for nonlinear relationships among multiple hazard factors. It is also hypothesized that predicting the dynamics of the integral hazard indicator will increase the available response time for addressing the development of an emergency situation. This is expected to reduce the number of false alarms in the monitoring system and improve the validity of warning and emergency signal generation. Thus, the proposed neuro-fuzzy method can serve as the intelligent core of a cyber-physical civil protection system, enabling a transition from reactive detection of hazardous events to proactive prediction of their occurrence and development. The structure of the proposed method is presented in Figure 1.

The operating principle of the neuro-fuzzy method structure for predicting and assessing the level of technological hazard (Fig. 1) is based on the continuous acquisition of data from sensors of the cyber-physical civil protection system that monitor temperature, gas concentration, smoke level, pressure, vibration, and other parameters characterizing the state of the facility. The acquired data undergo a preprocessing stage that includes normalization, filtering, extraction of informative features, and comprehensive fusion of heterogeneous sensor data. The processed information is then supplied to the neuro-fuzzy model, in which the fuzzy logic system performs fuzzification, fuzzy inference, and defuzzification, while the neural network uses historical data for learning and adaptive adjustment of the fuzzy model parameters. As a result of the joint operation of these components, an integral risk index ranging from 0 to 1 is generated, which is used to determine the current level of technological hazard and predict its changes over a specified time horizon.

The generated results are transmitted to the visualization, alerting, and decision support system, which provides the operator with recommendations regarding the necessary response measures. The feedback loop incorporated into the structure ensures the continuous input of new data and response

outcomes for further model refinement, enabling the neuro-fuzzy method to adapt to changes in the state of the monitored facility and the conditions under which technological hazards may arise.

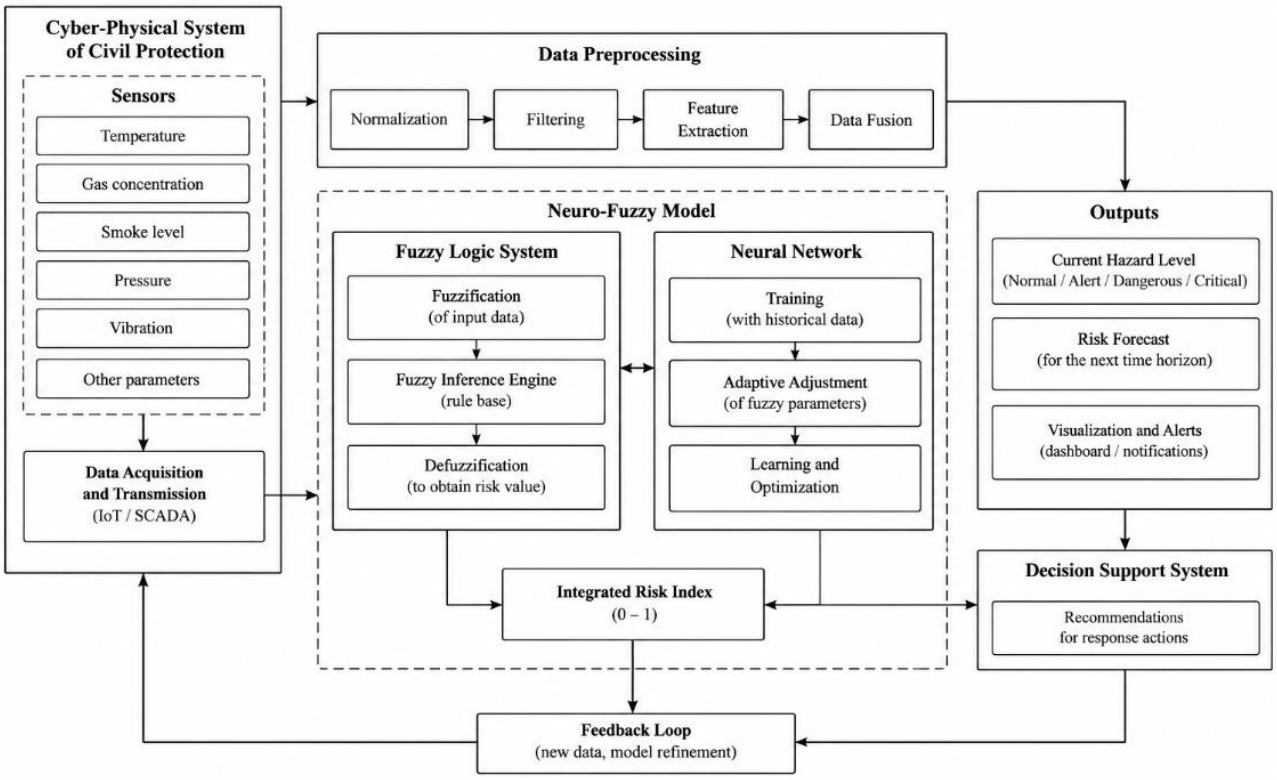

Figure 1 – Structure of the Neuro-Fuzzy Method for Predicting and Assessing the Level of Technological Hazard

An advantage of the developed structure is the integration of modern cyber-physical system technologies, IoT/SCADA, neural networks, and fuzzy logic, which enables comprehensive processing of heterogeneous sensor data in near-real-time. The combination of neural learning with fuzzy inference allows the model to be adaptively adjusted while accounting for process nonlinearity, data uncertainty, and complex relationships among technological hazard factors. The formation of an integral risk index and prediction of its dynamics enables a transition from conventional reactive monitoring to proactive detection of potentially hazardous states before the monitored parameters reach critical values. The decision support system makes it possible to transform the results of intelligent analysis into well-founded recommendations for response measures, thereby reducing the time between hazard detection and the adoption of appropriate management decisions. The use of a feedback loop ensures continuous accumulation of new data and adaptive refinement of the neuro-fuzzy model, allowing the proposed structure to be scaled and adapted to various critical and industrial infrastructure facilities.

CONCLUSIONS. The paper proposes a structure of a neuro-fuzzy method for predicting and assessing the level of technological hazard, which provides comprehensive processing of heterogeneous sensor data from cyber-physical civil protection systems by combining fuzzy inference with adaptive neural network learning. The formation of an integral risk index and prediction of its dynamics enable early detection of pre-emergency and hazardous states and facilitate a transition from reactive monitoring to proactive response to technological hazards. The proposed feedback loop provides adaptive refinement of the neuro-fuzzy model based on newly acquired data, thereby enhancing its applicability to various critical and industrial infrastructure facilities. Further research

should focus on experimental verification of the method, assessment of the accuracy and timeliness of technological hazard prediction, as well as investigation of its robustness to sensor data drift and distortion.

Reference

1. Barna, V., Ridzoňová, D., & Majlingová, A. (2026). Integrating Climate Change Adaptation, Disaster Risk Reduction, and Civil Protection for Sustainable Development: A Comparative Analysis of Central European Strategies. Sustainability, 18(9), 4548. https://doi.org/10.3390/su18094548

2. Yevsieiev V., Sezonova I., Artem Bronnikov. Synergy of Humans and Artificial Intelligence in the Management of Civil Protection Forces in Accordance with the Industry 5.0 Concept // Oxford 2026: Science and Education Today : proceedings of the International scientific and practical conference (July 17-19, 2026). - Oxford, United Kingdom : 2026. - Pp. 57-60. https://doi.org/10.64828/conf-140-2026

3. Modarres, MohammadReza and Almeida, Miguel and de Diego, Emilio and Torres, Luis and Asensio Martínez, Laura and Miranda, A. I., A Knowledge-Based Decision Support Framework for Multi-Hazard and Cascading NaTech Risk Assessment: Systematic Review and Multi-Criteria Evaluation. Available at SSRN: http://dx.doi.org/10.2139/ssrn.7003022

4. Yevsieiev V., Sezonova I., Demska N. Digital Twins and Cyber-Physical Systems as the Foundation for the Transformation of Civil Defense in the Context of Industry 5.0 // Paris Science and Education Forum : proceedings of the International scientific and practical conference (July 10-12, 2026). – Paris, France : - Pp. 12-14. https://doi.org/10.64828/conf-139-2026

5. Yevsieiev V., Stytsenko T. Intelligent Situational Awareness Systems for Civil Safety Based on Industry 5.0 Technologies // In VII Correspondence International Scientific and Practical Conference Science in Motion: Classic and Modern Tools and Methods In Scientific Investigations held on July 24th, 2026. P.181-184. DOI : https://doi.org/10.36074/grail-of-science.24.07.2026.

6. Benetti, L. (2026). Cyber Intelligence and Critical Infrastructure Protection: An Integrated Framework for Defending Against Hybrid Cyber-Physical Threats. Available at SSRN 6730318. https://dx.doi.org/10.2139/ssrn.6730318

7. Reza, M. H., Sibly, M. N. B., Rabbani, S. G., Sadi, S. H., Ahamed, M. F., Shafi, F. B., ... & Chowdhury, M. E. (2026). A comprehensive review of convolutional neural networks: foundations, enhancements and applications. Neural Computing and Applications, 38(4), 56. https://doi.org/10.1007/s00521-025-11827-w

8. Nevliudov I. Sh., Yevsieiev V., Sotnik S. Implementing Industry 5.0 Technologies in Civil Safety Systems for Intelligent Emergency Management // In Proceedings of the XII International Scientific and Theoretical Conference, July 17, 2026. San Francisco, USA: International Center of Scientific Research. -281. P. 85-88. https://doi.org/10.36074/scientia-17.07.2026

9. Michaloglou, A., Papadimitriou, I., Gialampoukidis, I., Vrochidis, S., & Kompatsiaris, I. (2026). Physics-informed neural networks in materials modeling and design: A review. Archives of Computational Methods in Engineering, 33(4), 5223-5260. https://doi.org/10.1007/s11831-025-10448-9

10. Abu-Jassar, A. T., Attar, H., Amer, A., Lyashenko, V., Yevsieiev, V., & Solyman, A. (2025). Development and investigation of vision system for a small-sized mobile humanoid robot in a smart environment. International Journal of Crowd Science, 9(1), 29-43. https://doi.org/10.26599/IJCS.2023.9100018

11. Gurin, D., Yevsieiev, V., Maksymova, S., & Alkhalaileh, A. (2024). Mobilenetv2 neural network model for human recognition and identification in the working area of a collaborative robot. Multidisciplinary Journal of Science and Technology, 4(8), 5-12.

12. Nevliudov, I., Yevsieiev, V., Maksymova, S., Gopejenko, V., & Kosenko, V. (2025). Development of mathematical support for adaptive control for the intelligent gripper of the collaborative robot manipulator. Advanced Information Systems, 9(3), 57-65. https://doi.org/10.20998/2522-9052.2025.3.07