INTELLIGENT METHOD FOR DYNAMIC EMERGENCY RISK ASSESSMENT AT CRITICAL INFRASTRUCTURE FACILITIES BASED ON DIGITAL TWIN

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

Annotation: The paper proposes an intelligent method for dynamic emergency risk assessment at critical infrastructure facilities based on Digital Twin technology, which provides continuous synchronization between the physical and digital states of an object, simulation of hazardous event development scenarios, and intelligent risk prediction. The proposed method involves the formation of a dynamic risk index based on current and predicted hazard factors, early detection of critical states, and generation of recommendations for decision support, thereby creating the prerequisites for a transition from reactive response to proactive safety management of critical infrastructure.

Key words: Digital Twin; critical infrastructure; emergency; dynamic risk assessment; risk prediction; artificial intelligence; decision support.

ІНТЕЛЕКТУАЛЬНИЙ МЕТОД ДИНАМІЧНОГО ОЦІНЮВАННЯ РИЗИКІВ НАДЗВИЧАЙНИХ СИТУАЦІЙ НА ОБ'ЄКТАХ КРИТИЧНОЇ ІНФРАСТРУКТУРИ НА ОСНОВІ DIGITAL TWIN

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

Анотація: У роботі запропоновано інтелектуальний метод динамічного оцінювання ризиків надзвичайних ситуацій на об’єктах критичної інфраструктури на основі технології Digital Twin, який забезпечує безперервну синхронізацію фізичного та цифрового станів об’єкта, моделювання сценаріїв розвитку небезпечних ситуацій та інтелектуальне прогнозування ризиків. Запропонований метод передбачає формування динамічного індексу ризику на основі поточних і прогнозованих факторів небезпеки, раннє виявлення критичних станів та формування рекомендацій для підтримки прийняття рішень, що створює передумови для переходу від реактивного реагування до проактивного управління безпекою критичної інфраструктури.

Ключові слова: Digital Twin; критична інфраструктура; надзвичайна ситуація; динамічне оцінювання ризиків; прогнозування ризиків; штучний інтелект; підтримка прийняття рішень.

The relevance of the research is determined by the need to improve the effectiveness of forecasting and dynamic assessment of emergency risks at critical infrastructure facilities, whose operation is characterized by complex technological processes, variability of parameters, and the influence of multiple interrelated hazard factors. Traditional risk assessment methods are predominantly based on static indicators and predefined threshold values, which limits their ability to detect pre-emergency states in a timely manner and predict the development of hazardous events. The use of **Digital Twin** technology makes it possible to create an up-to-date digital representation of a physical facility, continuously update its state based on sensor data, and simulate possible emergency development scenarios. The integration of Digital Twin technology with intelligent data analysis algorithms creates the prerequisites for calculating a dynamic risk index, predicting its changes over time, and detecting trends indicating the transition of a facility toward a critical state at an early stage. The development of such a method will facilitate the transition from reactive response to proactive

risk management and improve the validity of decision-making in civil protection systems. The structural diagram of the intelligent method for dynamic emergency risk assessment at critical infrastructure facilities based on Digital Twin is presented in Figure 1.

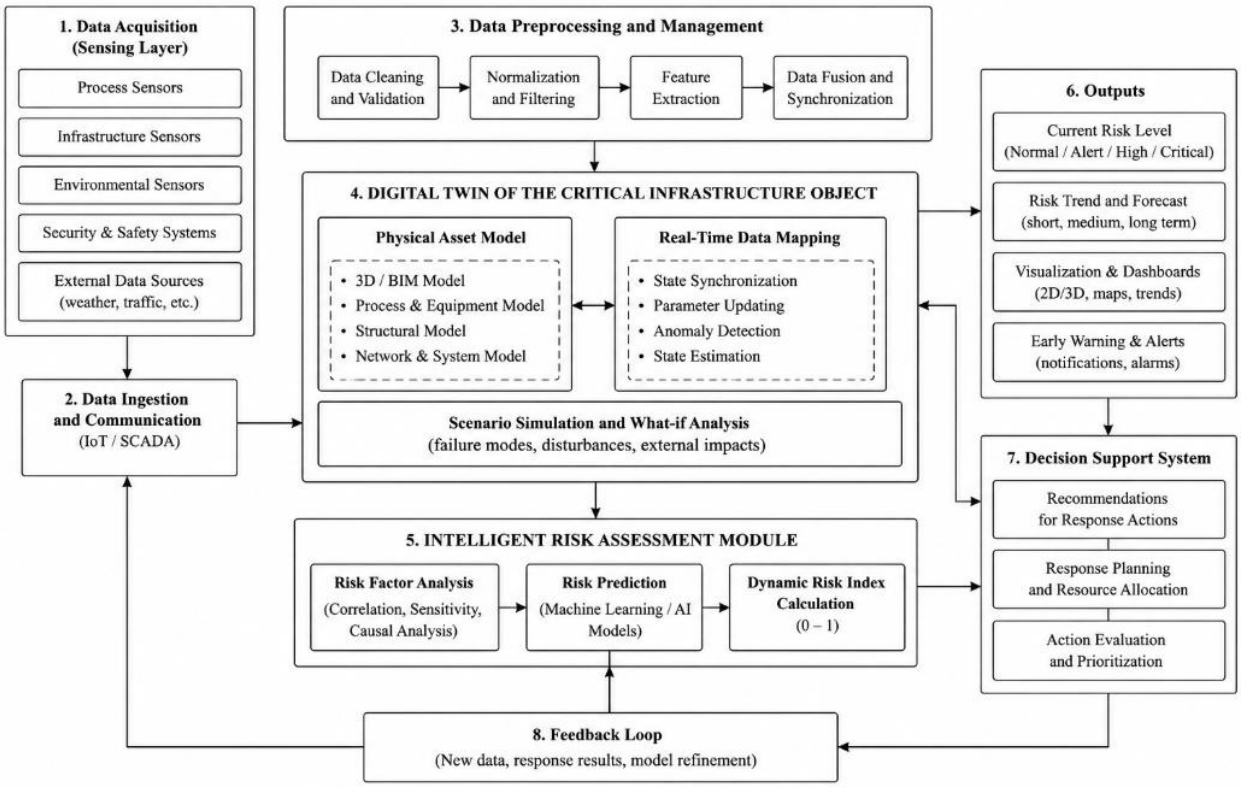

Figure 1 – Structural Diagram of the Intelligent Method for Dynamic Emergency Risk Assessment at Critical Infrastructure Facilities Based on Digital Twin

The operating principle of the intelligent method for dynamic emergency risk assessment at critical infrastructure facilities (Fig. 1) is based on the continuous interaction between the physical facility, its Digital Twin, the intelligent risk assessment module, and the decision support system. The Data Acquisition (Sensing Layer) block is designed to obtain primary information about the current state of the facility using technological, infrastructure, and environmental sensors, safety systems, as well as external data sources concerning weather, transportation, and other influencing factors. The Data Ingestion and Communication block ensures the transmission of the acquired information through the IoT/SCADA infrastructure and establishes an information link between the physical facility and its digital representation. The Data Preprocessing and Management block performs data validation and cleaning, normalization, filtering, informative feature extraction, data fusion, and temporal synchronization of heterogeneous information streams, thereby forming a consistent set of input parameters for further analysis. The central component of the method is the Digital Twin of the Critical Infrastructure Object block, which creates an up-to-date digital representation of the critical infrastructure facility and integrates the physical asset model with a real-time data mapping mechanism. The Physical Asset Model component includes a 3D/BIM model, models of technological processes and equipment, structural models, and models describing the interrelationships between the facility's systems, while Real-Time Data Mapping ensures synchronization between the physical and digital states, parameter updating, anomaly detection, and assessment of the facility's current condition. Based on the updated Digital Twin, the Scenario Simulation and What-if Analysis component simulates potential failures, deviations from

technological operating modes, and external impacts, making it possible to investigate potential emergency development scenarios without direct intervention in the physical facility.

The simulation results are transmitted to the Intelligent Risk Assessment Module, which is designed for intelligent analysis of the current and predicted states of the critical infrastructure facility. Within this module, the Risk Factor Analysis component identifies relationships among hazard factors using correlation, sensitivity, and cause-and-effect analysis, after which the Risk Prediction block applies Machine Learning and Artificial Intelligence models to predict the probable development of hazardous processes. Based on the obtained results, the Dynamic Risk Index Calculation component generates a dynamic risk index within a normalized range from 0 to 1, whose value changes according to the current state of the facility and the predicted development of the situation. The Outputs block transforms the results of intelligent analysis into information suitable for operational use by determining the current risk level according to the Normal, Alert, High, and Critical states, generating short-, medium-, and long-term forecasts, visualizing the results, and providing early warnings of a potential emergency. The obtained assessments are transmitted to the Decision Support System, where recommendations for response measures are generated, actions and allocation of required resources are planned, and potential management decisions are evaluated and prioritized. The final element is the Feedback Loop, which returns new sensor data, the results of implemented response measures, and information on the actual development of the situation to the information and intelligent processing loops of the method for further model refinement. Thus, the closed-loop cycle "physical facility → data → Digital Twin → scenario simulation → intelligent risk assessment → prediction → decision support → feedback" provides continuous dynamic assessment of technological risks and enables a transition from reactive response to an emergency that has already occurred toward proactive prediction and prevention of its development.

The main advantage of the proposed method is the use of Digital Twin technology for continuous synchronization between the physical and digital states of a critical infrastructure facility, which makes it possible to incorporate up-to-date sensor data and investigate potential emergency development scenarios without direct intervention in the real facility. The integration of Machine Learning and Artificial Intelligence methods enables intelligent analysis of relationships among hazard factors, prediction of their development, and calculation of a dynamic risk index ranging from 0 to 1, which adaptively changes according to the current and predicted states of the facility. An important advantage is the ability to generate short-, medium-, and long-term forecasts, detect critical states at an early stage, and automatically generate warnings, thereby improving the timeliness of response to potential threats. The integration of assessment results with the Decision Support System makes it possible to generate response recommendations, plan necessary actions, allocate resources, and prioritize management decisions. The closed feedback loop enables model refinement based on new data and response outcomes, allowing the proposed method to facilitate a transition from static and reactive risk assessment to continuous proactive safety management of critical infrastructure facilities.

CONCLUSIONS. As a result of the research, a structure of an intelligent method for dynamic emergency risk assessment at critical infrastructure facilities is proposed, based on Digital Twin technology, continuous acquisition of sensor data, and intelligent analysis and prediction tools. The use of a Digital Twin ensures synchronization between the physical and digital states of the facility, simulation of possible hazardous situation development scenarios, and calculation of a dynamic risk index taking into account current and predicted hazard factors. The integration of the intelligent risk assessment module with the Decision Support System creates the prerequisites for early detection of critical states, prediction of emergency development, and well-founded selection of appropriate response measures. The proposed approach enables a transition from static and reactive risk assessment to continuous proactive safety management of critical infrastructure facilities.

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