

levels—from digital design to enterprise management systems – and to overcome the remaining barriers of cost, standards, and workforce training.

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INTELLIGENT MICROCLIMATE CONTROL: FROM REACTIVE ALGORITHMS TO PREDICTIVE MODELS

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The paper discusses the limitations of reactive algorithms for microclimate control in industrial premises and justifies the need for a transition to predictive models. An analysis of traditional and intelligent approaches is carried out, and the mathematical formulation of the microclimate forecasting problem is presented. The use of the NNARX architecture and its combination with fuzzy logic for the development of a hybrid control system is proposed. The advantages of this approach for improving the stability of technological processes and the energy efficiency of production are demonstrated.

Microclimate control systems in industrial premises have traditionally been built on the basis of reactive algorithms, which involve threshold-based switching on or off of equipment depending on the actual values of environmental parameters. This approach is simple in terms of implementation; however, it does not take into account the dynamic nature of processes occurring under industrial conditions. As a result, control actions are performed with a delay relative to environmental changes, which leads to periodic fluctuations of temperature, humidity, and other indicators around the set values.

The microclimate in industrial facilities not only provides comfortable conditions for personnel but also determines the stability of technological processes and the reliability of equipment operation. Deviations of temperature or humidity from optimal values may result in reduced product quality, increased defects, and higher energy consumption. In high-tech industries, the microclimate often acts as a critical parameter that directly affects the efficiency of the entire system; therefore, improving methods of its maintenance is an important direction in the development of modern automated control systems.

The inefficiency of reactive algorithms also manifests itself in increased energy consumption and instability of technological processes. In modern production, where the microclimate is a key factor for product quality, equipment reliability, and personnel safety, such limitations become critical. This necessitates the transition to intelligent models capable of predicting parameters and generating proactive control actions, thereby enhancing the efficiency and stability of cyber-physical systems operating in industrial environments.

The study focuses on identifying the limitations of traditional microclimate control methods and finding ways to overcome them using intelligent models. The task is to analyze reactive algorithms and demonstrate the reasons for their insufficient effectiveness in industrial settings. In addition, the potential of neural networks for forecasting environmental parameters and improving control accuracy is examined. An important aspect is the justification of the advantages of a hybrid approach that combines the capabilities of the NNARX model with the adaptability of fuzzy logic systems, since such integration ensures the transition from reactive to proactive control in industrial cyber-physical systems.

The research is aimed at analyzing the evolution of microclimate control methods in industrial conditions—from reactive algorithms to predictive models. Traditional threshold schemes, despite their implementation simplicity, show low efficiency due to reaction delays and the inability to account for complex dynamic processes. An alternative is the use of neural networks capable of reproducing nonlinear dependencies and predicting future system states. The general task of microclimate forecasting can be represented as a mapping between previous system states and external influences, taking the form of a nonlinear dependence:

$$y(t+1) = F(y(t), y(t-1), \dots, u(t), u(t-1), \dots)$$

where $y(t)$ – vector of microclimate parameters (temperature, humidity, gas mixture composition), a $u(t)$ – vector of control actions and external factors.

Among the architectures applied to solving such problems, multilayer perceptrons are capable of approximating nonlinear dependencies; however, they do not take into account the temporal context. Recurrent networks make it possible to capture short-term dependencies, but they have limitations when trained on long time series.

The analysis shows that multilayer perceptrons are suitable for approximating complex nonlinear dependencies, but their effectiveness decreases due to the absence of mechanisms for accounting for temporal sequences. Recurrent networks partially overcome this limitation, but training stability issues complicate their application in industrial conditions. In contrast, the NNARX architecture has a natural ability to represent system inertia and external disturbances, which makes it more reliable and resistant to environmental changes.

The most suitable architecture turned out to be NNARX, which combines an autoregressive structure with the ability to account for exogenous inputs. Practical results of applying NNARX demonstrate that this architecture provides more stable maintenance of environmental parameters and reduces fluctuations in temperature and humidity compared to traditional algorithms. As a result, the system’s energy consumption decreases, product quality improves, and the equipment service life is extended. Considering external factors such as ambient temperature or the operation of technological installations enables the model to adapt to changing production conditions and ensure more reliable operation of microclimate systems.

Within cyber-physical systems, the NNARX model can be integrated with sensor networks and real-time data acquisition systems. This makes it possible to obtain data streams from different technological zones and generate consistent forecasts for complex industrial objects. The use of such an architecture creates the foundation for decision support systems that combine data analysis with the automatic generation of optimal control actions. Additional integration of NNARX with fuzzy logic systems ensures the formation of control actions based on accurate forecasts, creating prerequisites for the transition from reactive to proactive control.

Table 1 summarizes the key characteristics of different approaches to microclimate control.

The comparative analysis demonstrates a consistent evolution of approaches: from simple reactive algorithms, which operate only after parameter deviations occur, to hybrid models capable of combining prediction and adaptive control. Such integration enables the transition from static regulation to a proactive strategy that accounts for future changes in conditions and minimizes the risk of production process instability. The combination of NNARX with fuzzy logic systems allows neural network forecasts to be transformed into flexible control signals that account for uncertainty and incomplete input data. This approach is particularly effective in industrial conditions, where microclimate parameters often change under the influence of unpredictable factors. The hybrid model ensures adaptability that cannot be achieved solely through reactive or classical algorithms.

Table 1. Comparison of approaches to microclimate control.

Approach	Characteristics	Efficiency in Production
Reactive algorithms	Simplicity, low cost, absence of forecasting	Low stability, excessive energy consumption
Neural network models (MLP, RNN)	Consideration of nonlinearities, ability to work with time series	Better forecasting, but limited adaptability
NNARX	Autoregressive structure with exogenous inputs, reproduction of system inertia	High forecasting accuracy
NNARX+FLC	Combination of forecasting and adaptive control	Proactive and stable control

The obtained results confirm the necessity of moving from traditional reactive algorithms to intelligent methods of forecasting and controlling the microclimate. Threshold-based systems that operate by switching equipment on and off after exceeding permissible limits proved insufficiently effective in

industrial processes due to parameter fluctuations and excessive energy consumption. In contrast, the use of neural networks makes it possible to generate forecasts of environmental states and provides the foundation for proactive control strategies.

Among the considered architectures, NNARX has proven to be the most suitable, as it combines temporal context with the influence of exogenous factors, thereby accurately reproducing the dynamics of the production environment. The integration of this model with fuzzy logic forms a hybrid system that combines forecasting accuracy with the adaptability of control actions. This approach ensures more stable functioning of cyber-physical systems in industrial conditions, increases energy efficiency, and reduces dependence on the human factor.

Thus, the feasibility of using the hybrid NNARX+FLC architecture as a promising direction in the development of intelligent microclimate control has been substantiated. Further research should be aimed at testing the operation of such a system under real production conditions and implementing mechanisms of adaptive real-time learning.

The further development of research in this direction should be associated with the integration of hybrid NNARX+FLC models into modern industrial automation systems, particularly at the SCADA and MES levels. This will not only ensure the stability of microclimate parameters but also create a unified information environment for monitoring and optimizing technological processes. Another important task for future work is the implementation of real-time adaptive neural network learning mechanisms, which will contribute to improving energy efficiency and reducing operating costs in industrial conditions.

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EPOKG AS DYNAMIC STRUCTURAL LAYER FOR ADAPTIVE ML IN BPM

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Abstract. *This paper proposes a dynamic structural layer (EPOKG) for adaptive machine learning and process automation in BPM, enabling dynamic input of process and organizational context into GNN-based models. The approach unifies process structure, roles, and temporal versions into a single semantic graph, improving prediction accuracy and consistency across evolving business processes.*

Problem statement. In modern organizations, business processes constantly evolve under regulatory changes, strategic shifts, or reorganizations. As Van der Aalst (2016) noted, “there is no