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Prospects for the Implementation of Cyber-Physical Systems for Monitoring and Control of Microclimate in the Context of Industry 4.0

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Abstract. The paper examines the prospects and prerequisites for the implementation of cyber-physical systems for monitoring and controlling the microclimate of industrial premises in the context of industrial digital transformation and the Industry 4.0 concept. It is shown that traditional automatic control systems based on PID controllers are limited in their ability to account for the nonlinearity, inertia, and multifactor nature of microclimate formation processes. The feasibility of transitioning to intelligent control systems that integrate sensor networks, computational modules, and actuators into a unified cyber-physical architecture is substantiated. A parametric mathematical model of the microclimate is presented, which formalizes the relationships between temperature, humidity, air gas composition, and actuating mechanisms while considering external disturbances. The role of neural network models of the NNARX type as the predictive core of an intelligent control system is revealed. It is demonstrated that the integration of predictive models into the structure of a cyber-physical system enables a transition from reactive to predictive control, which contributes to improving the stability of environmental parameters, reducing energy consumption, and increasing the reliability of industrial processes [1].
Keywords: *cyber-physical system, microclimate, Industry 4.0, intelligent control, parametric model, NNARX, energy efficiency, predictive control.*

Ensuring stable microclimate parameters in industrial premises is one of the key conditions for the efficient functioning of modern industrial enterprises. The microclimate of the production environment, determined by a set of parameters such as temperature, relative humidity, gas composition, and air exchange intensity, directly affects the stability of technological processes, product quality, energy efficiency of production, and occupational safety of personnel. Under modern industrial conditions, microclimate parameters are not constant but change under the influence of a wide range of external and internal factors, including fluctuations in outdoor temperature, seasonal humidity changes, thermal loads from technological equipment, operating modes of ventilation systems, and the intensity of production processes. Such dynamics make it impossible to effectively use traditional reactive control algorithms and necessitate the transition to more flexible and adaptive approaches.

Traditional microclimate control systems, based on classical PID controllers and relay control schemes, are focused on stabilizing individual environmental parameters by generating control actions based on the current deviation from the setpoint. Such systems demonstrate satisfactory accuracy under stable conditions; however, their effectiveness significantly decreases in the presence of nonlinear relationships between microclimate parameters, time delays between the control action and the actual change in the environmental state, as well as under the simultaneous influence of multiple internal and external disturbances. The response of the production environment to changes in ventilation intensity or heating power is not instantaneous and largely depends on the thermal inertia of the premises, the spatial distribution of zones, and the nature of technological loads. The presence of transport delay leads to overshoot, oscillatory processes, and excessive energy consumption, which is especially critical for industries with strict requirements for maintaining environmental parameters.

The development of the Industry 4.0 concept and the digitalization of industry create fundamentally new prerequisites for addressing these problems. Cyber-physical systems, which integrate physical control objects, sensor infrastructure, computational resources, and communication networks into a unified information and control space, enable the implementation of adaptive and predictive microclimate control algorithms in real time. Unlike traditional automated systems, a cyber-physical system forms a closed intelligent control loop in which data from sensors measuring temperature, humidity, gas concentration, and air exchange rate continuously enter the computational core, where predictive estimates of the future state of the environment are generated and optimal control actions for actuating mechanisms are formed. Such an architecture provides not only a response to current deviations of parameters but also the possibility of preventing their occurrence through the proactive generation of control actions.

A central element of the architecture of a cyber-physical microclimate control system is a parametric mathematical model that formalizes the relationships between the main environmental parameters, actuating mechanisms, and external disturbances. Within the framework of this study, the microclimate is described as a parametric function that takes into account the influence of variable factors:

$$MicroClimate = f(T_{in}, T_{out}, H_{in}, H_{out}, GasMix, N_p, Actuators, D) \qquad (1)$$

where T_{in} *– indoor air temperature,* T_{out} *– outdoor air temperature,* H_{in} *– indoor air humidity,* H_{out} *– outdoor air humidity,* $GasMix$ *– total concentration of gas components,* N_p *– number of people in the premises,* $Actuators$ *– set of actuating mechanisms,* D *– disturbances caused by technological processes and environmental factors.*

The proposed model provides a universal formalized description of microclimate dynamics, allowing the control system to be adapted to different temperature ranges and types of industrial environments. An important component of the model is the decomposition of parameters, which makes it possible to divide a complex multifactor control problem into a set of interconnected subproblems, each responsible for regulating a specific parameter while taking into account its physical nature and dynamic characteristics.

Actuators within the cyber-physical system play a key role in implementing control actions. The main actuating mechanisms include heating systems that maintain the air temperature within a specified range; cooling systems that are activated when temperature thresholds are exceeded, taking into account humidity levels and outdoor temperature; variable-speed fans that allow precise adjustment of air exchange intensity depending on deviations in temperature, humidity, and gas concentration; as well as automated air inlet dampers that compensate for the volume of exhaust air and maintain stable pressure within the premises. The integration of these mechanisms into a unified cyber-physical architecture ensures coordinated and synchronized operation of all microclimate control subsystems [3].

The transition from reactive to predictive control within a cyber-physical system is achieved through the integration of neural network forecasting models, in particular the NNARX architecture. This model combines an autoregressive structure that takes into account several previous values of the predicted variable with the ability to include exogenous signals that characterize external and internal influences on the microclimate. Formally, the model is described by the following relation:

$$y(t+1) = F(y(t), y(t-1), \ldots, y(t-ny), u(t), u(t-1, \ldots, u(t-nu)) \quad (2)$$

where y *— predicted microclimate parameter,* u *— vector of exogenous input variables,* ny *and* nu *— delay orders of the output and input variables, respectively,* F *— a nonlinear function implemented by a neural network. The use of the autoregressive component provides the formation of the model's internal "memory," which makes it possible to reproduce the inertial properties of thermal and ventilation processes and to account for the cumulative nature of changes in microclimate parameters.*

The practical implementation of a cyber-physical microclimate control system involves the close integration of hardware and software components. The hardware level includes sensors for temperature, humidity, and CO_2 concentration, as well as controllers for controlling actuating mechanisms. The software level implements algorithms for data acquisition and preprocessing, the NNARX forecasting model, and decision-making modules based on fuzzy logic. The integration of these levels ensures the operation of a closed-loop intelligent control system in which the system can adapt to changing production conditions through self-learning and periodic updating of the parameters of the predictive model.

Particular attention should be given to the issue of energy efficiency in the implementation of cyber-physical microclimate control systems. Traditional control systems often operate in an over-control mode, where actuators are activated with a delay relative to the moment when parameter deviations occur, leading to overshoot and additional energy consumption. Predictive control based on the NNARX model allows control actions to be generated in advance, before environmental parameter deviations reach critical levels. This ensures smoother operation of actuators, reduces the number of abrupt corrections, and decreases peak loads on heating, ventilation, and air conditioning systems [4].

A comparative analysis of traditional and intelligent approaches to microclimate control demonstrates the significant advantages of cyber-physical systems with intelligent forecasting. The generalized results of this comparison are presented in Table 1.

Table 1

Comparative characteristics of approaches to microclimate control in industrial premises

Criterion	**Traditional systems (PID)**	**Intelligent Cyber-Physical Systems (NNARX + FLC)**
Control principle	Reactive, based on current deviation	Predictive, based on the forecast of the future state
Accounting for non-linearities	Limited, linear approximation	Full, nonlinear neural network model
Adaptation to changing conditions	Requires manual re-tuning	Automatic adaptation through self-learning
Energy efficiency	Overshoot and energy consumption	Smooth control, reduction of peak loads
Real-time operation	High speed, limited adaptability	Balanced performance and adaptability
Scalability	Limited, tied to a specific object	Universal parametric model

As shown in the table, traditional PID systems provide high response speed but have limited adaptability when dealing with nonlinear and inertial control objects. Intelligent cyber-physical systems based on NNARX predictive models and fuzzy logic controllers provide a predictive control approach that allows the dynamics of processes to be taken into account, adapts to changing conditions, and ensures energy-efficient system operation. The universality of the parametric model makes it possible to apply the developed solutions to various types of industrial facilities without the need for significant restructuring of the control system architecture.

The practical implementation of cyber-physical microclimate control systems requires solving a number of engineering tasks, including ensuring reliable communication between sensors and the computational core, organizing the collection and preprocessing of measurement data, and integrating the predictive model with the controller in real time. The implementation of the NNARX model in the Python/Keras environment provides sufficient flexibility for configuring the neural network architecture and training it on experimental data, while integration with a microcontroller through appropriate interfaces enables real-time system operation.

An important aspect of implementation is also ensuring the stability and reliability of the system under conditions of incomplete and noisy input data. Sensor measurements in industrial environments may contain random fluctuations, short-term distortions, or anomalous values, which negatively affect prediction accuracy and the stability of control actions. To reduce the impact of these factors, it is advisable to apply methods for preventing neural network overfitting, including dropout in hidden layers, weight regularization, and training data augmentation. The combined use of these methods improves prediction stability and ensures the smoothness of control signals, which is critically important for the reliable operation of actuators [6].

The developed architecture of the cyber-physical microclimate control system has the potential for further development toward the creation of digital twins of industrial premises, which would enable virtual modeling and optimization of control modes without interfering with the real production process. The implementation of Edge AI methods for deploying predictive models directly at the controller level is also promising, as it reduces dependence on external computing resources and increases system responsiveness. Furthermore, adapting the system to the principles of the Industry 5.0 concept, which emphasizes a human-centered approach and sustainable production, opens additional opportunities for personalizing microclimate parameters according to the needs of personnel.

Conclusions. The paper examines the prospects for the implementation of cyber-physical systems for monitoring and controlling the microclimate of industrial premises within the framework of the Industry 4.0 concept. It is shown that traditional automatic control systems are limited in their ability to ensure effective microclimate control under conditions of nonlinearity, inertia, and the multifactor nature of processes. The feasibility of transitioning to intelligent cyber-physical systems that integrate parametric mathematical models, neural network-based forecasting using

NNARX, and fuzzy logic control into a unified architecture is substantiated.

The proposed parametric microclimate model provides a formalized description of the relationships between key environmental parameters and actuating mechanisms, enabling the development of universal control systems adaptable to various types of industrial facilities. It is demonstrated that integrating the NNARX predictive model into the structure of a cyber-physical system enables the transition from reactive to predictive control, thereby improving the stability of microclimate parameters, reducing energy consumption, and increasing the reliability of industrial processes.

Further research should be focused on the development of digital twins of industrial premises, the implementation of Edge AI methods for deploying predictive models at the controller level, and the adaptation of microclimate control systems to the principles of the Industry 5.0 concept, taking into account a human-centered approach and production sustainability.

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