- schemes for the functioning of a hybrid intelligent computer system, providing the possibility of semantic compatibility and sharing with other solutions at industrial enterprises in the context of the Industry 4.0 concept [6];
- algorithms for the synthesis of control feedback based on the use of neuroregulators;
- method of adaptive control of automated production systems in the presence of external control influences;
- software support for intelligent systems based on adaptation algorithms and the proposed method in real time.

The results provide a new constructive approach to the formalization of the technological cycle, based on the use of open semantic technologies for the design of intelligent systems, and the synthesis of feedback on the management of the production process using neural network modeling, which allows to:

- develop hybrid intelligent computer systems designed to solve problems of adapting the management of complex technical systems, in particular, the technological production cycle;
- ensure integration and semantic compatibility of the components of the control system model with other intelligent systems;
- search for optimal parameters for adapting control and stabilizing controlled variables of technological operations in specified ranges of permissible values.

The described tools make it possible to create flexible intelligent computer control adaptation systems (CCAS), which are a set of semantically compatible and easily replaceable components depending on the range of tasks being solved.

The interaction of the system and its corresponding solvers with the control rack of the automated technological system is carried out using means of software and hardware interface of production.

## III. Constructing components of a multi-level control system model in conditions of incomplete information

Optimization of the parameters of the technological cycle of automated production requires the development of effective control adaptation algorithms and methods for constructing neuroregulators that stabilize the parameters of technological operations, taking into account current information about the functioning of the object of study, random disturbances and external control influences, which are recorded during the operation of the control system controller and stored at the control rack automated control system (ACS) for the technological process (TP).

The structural diagram of the interaction of the components of the intelligent control adaptation system is presented in figure 1. A formal description of the control object is carried out based on the use of the ontology of the "probabilistic technological production processes" subject area. When implementing this approach, formalized knowledge is used to describe technological processes with probabilistic characteristics of technological operations and model technological processes.

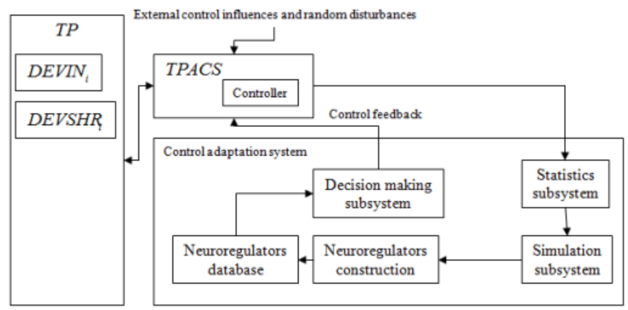


Figure 1: Diagram of interaction of the components of the intelligent control adaptation system

The formalization used is based on the scientific research of the authors in the field of simulation modeling of complex technical systems and implies the use of libraries of simulator units of technological operations integrated into the OSTIS ecosystem on the principles of semantic compatibility [7].

When the characteristics of technological operations of a control object are highly non-stationary, simulation models, neuroregulators and multi-step learning algorithms with better dynamic properties are used to build multi-level mathematical models.

As follows from the interaction diagram of the system components, the formation of control feedback comes down to the search for control adaptation that satisfies user-specified criteria, carried out according to the closed-loop principle, in which neuroregulator models are built on the basis of the collected statistics of the operation of the automated process control system and a collection of simulation models. The decision-making system, operating using the constructed neuroregulators, carries out in real time the formation of corrective influences on the controller of the automated control system of the TP.

The introduction of the Industry 4.0 concept at industrial enterprises is accompanied by the creation of a digital twin of the enterprise and the construction of a unified ontological production model, which is the core of comprehensive information services for the enterprise. One of the stages of building a digital twin model of an enterprise is the embedding of data on low levels of production, such as production processes and equipment [8].

## IV. Methodology for formalizing a technological system when stabilizing control parameters

In order to ensure the possibility of using an intelligent control adaptation system, knowledge about the technological process of an enterprise must be recorded in a formal knowledge representation language. The sources of such knowledge can be existing descriptions of the work of enterprises within the framework of accepted international standards (such as ISA 5.1, ISA88) [6], [9]–[11]. Thus, within the framework of the ISA-88 standard, a technological cycle is called a procedure, and a technological operation is called a phase.

If there is a known set of devices and maintenance of the technological cycle, as well as statistical data on their operation, it is possible to move on to simulation modeling of the technological process by replacing devices in the probabilistic network diagram (PND) describing the cycle with units simulating the operation of shared use and individual use devices. The operations present in the model can be implemented as a set of event simulator units and technological operations simulator units. Based on simulation models of the technological cycle constructed using the current operation statistics it is possible to construct neuroregulators that carry out corrections of the controller's control actions [12].

With this approach, the adaptive control system requires a minimum amount of initial information about the incoming signals, and the described formalization makes it possible to synthesize knowledge bases about an industrial enterprise and its technological processes based on the domain ontology within the framework of the Industry 4.0 concept of automation of industrial enterprises.

## V. Stabilization of control parameters based on an intelligent computer system

The basis for creating a hybrid intelligent control adaptation system is the idea of developing multi-level simulation models and mathematical models of neural network regulators [12] to solve problems of control optimization, constructing algorithms for synthesizing control feedback for the technological cycle depending on changes in the operating parameters of the controlled object.

The hybrid intelligent control adaptation system includes the following components:

- subsystem for processing and storing statistics of the operation of TP ACS;
- simulation subsystem;
- subsystem for constructing models of neuroregulators;
- database of constructed neuroregulators;
- decision-making subsystem.

TP operation statistics include the values of signals describing the state of TP devices, as well as the values of control signals. The statistics processing and storage subsystem is responsible for saving the historical values of signal data.

The simulation subsystem allows construction and execution of simulation models of a technological process and its control system based on the ontological model of production and the described formalization. Historical values saved by the subsystem for processing and storing performance statistics are used as initial data. Based on them, distribution functions are constructed for resources consumed by technological operations and reliability characteristics of equipment, stored in the knowledge base. Simulator units of the operation of devices for shared and individual use are the basis for creating TP simulation model.

The subsystem for constructing models of neuroregulators implements neural network modeling algorithms to find the optimal control adaptation strategy. Provided that there are known target values of correction signals (for example, in the case of manual data marking, or the presence of an existing high-quality regulator of the system regulator), a neuroregulator can be built using the collected statistics of the operation of the technological process and automated control system [13], [14]. In the absence of a regulator prototype, algorithms are used to search for the optimal policy for selecting actions in an environment built on the basis of a TP simulation subsystem [7], [12].

It should be noted that algorithms of this type allow to automate the search for an adaptation policy, taking into account the criteria specified by the system user for assessing the quality of the policy for selecting actions by the neuroregulator [12]. The target function of the neural network training algorithm may "reward" for reducing production costs and "fine" for equipment downtime, equipment failures or emergences based on the coefficients selected by system user.

Adaptive-critic-based schemes [15]–[20] for searching for an optimal control adaptation strategy have the potential to build an effective regulator of a control system due to the presence of a research element in the process of determining the optimal control policy, which can have a positive effect when solving problems with a complex structure of control decision-making space.

If necessary, a search for the optimal neural network architecture can also be carried out based on grid search or genetic algorithms [21] (Figure 3) using training and validation procedures to evaluate the candidate architectures. A feature of the latter approach is the tracking of genes using historical marks, which allows for the crossing of successful topologies, species division to preserve innovations, consistent movement from simple architectures to more complex ones.

The general scheme of the algorithm for constructing a neuroregulator is shown in 3

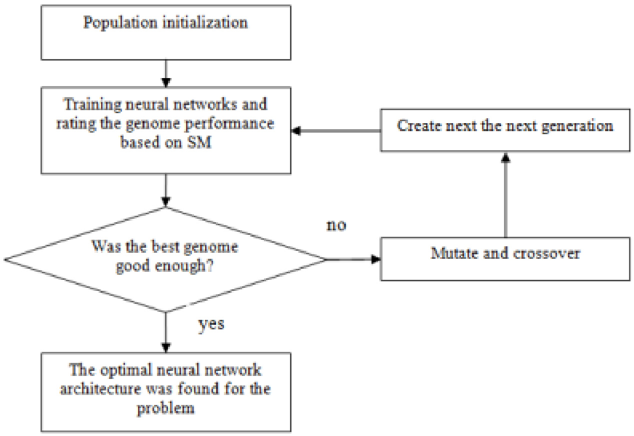


Figure 2: A genetic algorithm scheme to search for the optimal neural network architecture

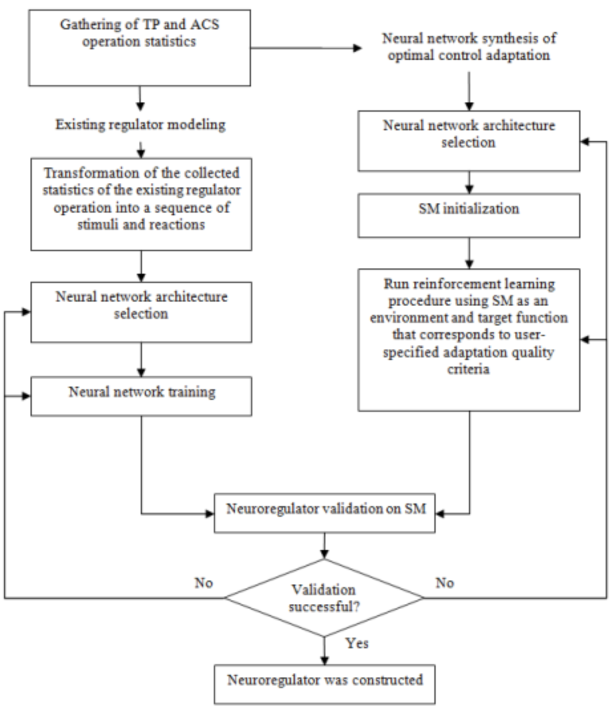


Figure 3: Neuroregulator synthesis algorithm scheme

Simulation modeling allows for model validation after training. Models of neuroregulators are saved to the database for further use or additional training using updated statistics.

The decision-making subsystem uses the constructed models of neuroregulators.

Adaptation of the technological cycle control is carried out on the basis of the operation of the constructed neuroregulator, which forms corrective influences on the process control system to prevent the range of changes in the components Ufh of the control vector variables Uh from going outside the allowed range.

Returning the values of control variables within the acceptable intervals is carried out by means of special adjustment means - initiating the launch of MTSO TP, which change the values of the components of the set of control variables Us or use equipment redundancy schemes.

Provided that appropriate hardware and software interface tools are available, it is possible to implement control adaptation in an automated mode, or to form a recommendation system used by personnel servicing the technological cycle.

Thus, when solving the problem of stabilizing the parameters of technological operations in real time, multilevel mathematical models were used, including neural network and simulation ones, and a new generation hybrid intelligent computer adaptive control system was implemented, created on the basis of open semantic technologies for designing intelligent systems [7].

## VI. An example of a simulation model of a probabilistic technological process control system

Simulation modeling of the interaction of control system elements and components of a probabilistic technological process can be carried out on the basis of synchronization schemes of their operation [7].

Simulation modeling of the implementation of a probabilistic technological process includes modeling of microtechnological operations associated with resource requests of a probabilistic nature, as well as possible changes in control variables U, and the operation of devices with possible device failures and their consequences.

The initial parameters for constructing a control system simulation model (CS SM) of an probabilistic technical process (PTP) are a set of parameters characterizing its composition and structure [7], including estimates of the distributions of various parameters of the TP, collected during its operation observation using appropriate software and hardware interface tools. In particular, these include the number of implementations of the simulation model N, the set Xi of PTP resource requests required to run the executive elements of the control system, the parameters of commutation of the executive elements with synchronization elements, input signal generators and the final operating element, configuration vector of the equipment composition and a set of reliability characteristics of the equipment.

Simulation modeling of control system of TP is based on the operation of a set of simulator units. Within the framework of OSTIS technology, the solution to the problem of operation of simulator units can be formalized on the basis of a multi-agent approach [7], when the SM of the PTP control system is implemented as a set of agents corresponding to simulator units that can exchange data through sc-texts.

Within the framework of the problem under consideration, the solver of the problem of operation of a simulator