Modeling of Industrial and Technological Processes in Complex Systems Based on Neuro-Fuzzy Petri Nets

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Abstract. For effective functioning within a complex system, industrial and technological processes are supported by appropriate information-analytical processes that ensure the collection and analysis of information, as well as modeling and making control decisions for the industrial and technological process. A variety of neuro-fuzzy Petri nets with temporal fuzzy neurons is proposed. An example of constructing a model of an industrial and technological process and the corresponding information-analytical processes is considered. The developed specialized software for modeling industrial and technological processes and the implementation of information-analytical processes is considered.

1. Introduction
The organization of the control process in modern complex technical systems is an urgent task, the solution of which is significantly hampered with an increase in information flows in such systems. Data sources can be both technical subsystems (temperature and pressure sensors, etc.) and operators of industrial and technological processes in the system. Often, specialists are simply not able to cover all the events and phenomena occurring within the system, affecting the system from the outside, as well as their combinations. There is a steady growth in the volume of information of different quality coming from heterogeneous sources, which is necessary for the analysis and development of control decisions in the course of the system's performance of the tasks set, associated with both the improvement of sensor technologies and communication lines, which leads to an increase in the frequency of sensor polling and the emergence of the possibility obtaining data from new sources.

Globalization and integration of complex technical systems lead to the fact that another complex technical system can serve as a source of data for one complex technical system. In this case, information can be transmitted between systems both constantly and in batch mode on a schedule, which leads to the need to consideration of the time factor. Unfortunately, information coming from other systems, which is necessary for the effective management of a complex system, may contain errors caused by a change
in the data format or technical problems in the source system. The ability to respond quickly to such situations is one of the factors for the effective management of a complex system.

A possible solution is the management of complex systems and manufacturing processes based on simulation. As a basis for modeling, it is proposed to use a neuro-fuzzy variety of Petri nets, which have established themselves as a convenient, visual, and at the same time mathematically rigorous formalism for modeling and analyzing complex systems and their inherent processes. They allow you to model processes, interaction protocols, and control processes with a sufficient degree of detail and visualization. Petri nets allow you to naturally describe synchronization, parallel-ism, conflict and causation, as well as to visualize the structure and functioning of complex systems.

2. Complex systems and their industrial and technological processes
As examples of complex systems, one can cite enterprises in the oil and gas industry, enterprises in the fuel and energy complex, energy supply systems (electricity, heat and water supply), systems for managing energy consumption and energy conservation of end consumers, as well as enterprises in the nitrogen industry.

The features of such complex systems are:
- the complexity of the structure, multicomponent, the presence of functional sub-systems that solve various target tasks, a large number of parameters characterizing the industrial and technological processes of the system;
- dynamic changes in the structure and parameters of the system;
- incomplete information about the functioning and state of the system;
- variety of external and anthropogenic impacts on the system;
- the presence of complex nonlinear relationships between parameters;
- the complexity of making management decisions to improve the efficiency of the system;
- limited opportunities for experimental studies of the system and ongoing processes;
- impossibility of using a unified approach to the creation of models of production-technical and information-analytical processes taking place in such systems.

The production and technical process is a process that includes a set of actions of people and tools of production, as well as actions to change and subsequently determine the state of the object of labor.

The features of industrial and technological processes in complex systems include the following:
- most industrial and technological processes are characterized by a continuous cycle;
- functional subsystems and their elements are interdependent, in addition, elements of one subsystem can be simultaneously elements of another subsystem;
- industrial and technological processes are energy and resource-intensive;
- some industrial and technological processes are classified as harmful and hazardous (from the point of view of man-made disturbances and emergencies);
- industrial and technological processes are highly complex, which increases as the requirements for operational efficiency increase;
- models of industrial and technological processes are poorly focused on solving management problems;
- industrial and technological processes are closely related to information-analytical processes.

3. Information-analytical processes in complex systems
Information-analytical processes are closely related to industrial and technological processes and are necessary to ensure the functioning of complex systems. Information-analytical processes include the processes of collecting, processing, generalizing, assessing and predicting the state of the system, developing informed management decisions, assessing their feasibility, efficiency and resource conservation.

They are characterized by:
- the need to process large volumes of heterogeneous semi-structured information;
the need to consider the specifics of the system of non-linearly dependent generalized and partial indicators;
high dynamics of changes in systemic and external factors affecting the effective-ness of management.

In complex systems, a large number of information-analytical processes are per-formed in parallel, differing not only in the direction of the data flow (input and output of information), but in orientation to various, both intersecting and independent subject areas within the framework of a common complex system.

In most complex systems, the number of processes is measured in hundreds and thousands, and their design is carried out by experts in various fields [11].

Various approaches are used to describe and design information-analytical processes in complex systems. The faster and more accurately the information-analytical process is developed and modified, and the information-analytical processes that require adjustment are identified, the less time a complex system will spend on adapting to changed conditions.

4. Models and methods for analysis and control of complex systems
To reduce the time and material costs associated with the development or modification of information-analytical processes caused by changes in the parameters of the system, the external environment or changes in the parameters of information-analytical or industrial and technological processes, it is advisable to use an approach that involves modeling such processes. Modeling provides tools for in-depth analysis of the processes running in the system, as well as the ability to assess the impact on the system or its environment of changes in one or another information-analytical process.

Process modeling is also an important step for analyzing and managing the developed process. The use of modeling helps to detect defects in the process, its bottle-necks, and clarify the complexity of the process.

Existing models designed for the analysis and management of complex technical systems are usually cumbersome and difficult to analyze, or their analysis takes a lot of time. Most of these models do not have sufficient flexibility and adaptability to changing conditions, and also do not consider the influence of environmental factors. Typical neuro-fuzzy models, as a rule, are not focused on analyzing the states of the analyzed processes and are not focused on adapting to constantly changing industrial and technological processes [2], [3].

In most cases, the problems of modeling and control of such systems are solved separately from each other, namely, the existing models are not focused on analysis, reasonable choice and implementation of control actions (measures) in the course of industrial and technological processes.

It is possible to formulate requirements for models and methods of analysis and management of complex systems:
• taking into account the hierarchical nesting of processes;
• taking into account the state of processes and their development in time;
• flexible task and change of conditions (including temporary ones) of process control;
• consideration of restrictions and risks (economic, man-made and others) of disruption of industrial and technological processes;
• taking into account the influence of uncertainty of systemic and external factors;
• taking into account the close interdependence of production-technical and information-analytical processes;
• the ability to quickly change the structure and parameters of the model when changing industrial and technological and/or information-analytical processes.

5. Using a Petri net for modeling processes in a complex system
One of the main advantages of the Petri nets apparatus is that they can be presented both in graphical form (this provides clarity) and analytical (this allows automating the process of their analysis) [10]. In
the graphical interpretation, a Petri net is a graph of a special kind [12], consisting of two types of vertices: positions and transitions connected by oriented arcs (branches), and each branch can connect only vertices of different types (a position with a transition or a transition with position) [9], [13].

Within the framework of the approach for modeling and developing processes in a complex system, it is proposed to use varieties of Petri nets, including the temporal neuro-fuzzy neurons of Kwan and Cai.

The expediency of using neuro-fuzzy components in modeling the processes occurring in most complex systems is due to:

- incomplete information about a complex system (for example, it is impossible to accurately determine the thickness of the vessel wall at a given time);
- uncertainty of information that enters the system;
- a significant part of information about the system may be fuzzy and insufficiently defined to be expressed by mathematical dependencies;
- information about a complex system is available in the form of expert data or a heuristic description of the functioning processes.

All the fuzzy things that have been dealt with in knowledge engineering so far can be classified as follows:

- non-determinism of conclusions;
- polysemy;
- unreliability;
- incompleteness;
- fuzziness or imprecision.

The expediency of using neuro-fuzzy components is due to one of the following situations: either the system is so complex that its mathematical model in the traditional sense cannot be built, or there is a model, but its analytical calculation requires significant resources [4].

One of the main advantages of using neuro-fuzzy components is the ability to identify patterns in the data, their generalization, and the main disadvantage is the impossibility of presenting a functional relationship between input and output. Another drawback is the difficulty of forming a representative sample, a large number of training cycles, and the difficulty of determining the size and structure of the neural network.

The use of neuro-fuzzy components can reduce or eliminate the influence of the uncertainty that exists in a complex system [5]. Thanks to the ability to set fuzzy rules, a complex system in which a neuro-fuzzy component is used becomes more efficient and adaptive.

A classic fuzzy neuron can have several outputs, the output values form the degree of membership in some fuzzy sets (Fig. 1) [6].

![Fuzzy neuron](image)

**Figure 1.** Fuzzy neuron.

The information in the system can arrive with a delay or irregularly. The delay can be associated with both preliminary analyzes and human activity in the system. A person in the system can have the following properties: to slowly switch from one type of task to another, to start performing the functions
assigned to him untimely, with some delay. The use of temporal inputs in a neuron allows one to consider the situations when the information at the inputs of a neuron can come with a certain delay. The use of temporality allows you to change the logic of the sequence of actions, for example, if the data arrived with a delay (or did not arrive at all), then modify the algorithm taking into account the risks.

Temporal neurons are extensions of regular neurons, allowing the processing of dynamic information [1]. Neuro-fuzzy components built using temporal neurons have a more complex architecture and, as a result, more complex learning algorithms.

To consider the state of processes and their development in time, a temporal modification of the neuron of Kwan and Cai is proposed (Fig. 2).

The graph (Fig. 3.) shows the dependence of the forecast accuracy of the neuro-fuzzy network on the number of learning epochs. The solid line represents a neural network built using modified Kwan and Cai neurons using temporal inputs, the dotted line - using the classic Kwan and Cai neurons.

**Figure 2.** Fuzzy neuron with temporal inputs.

**Figure 3.** Fuzzy neuron with temporal inputs. Dependence of the forecast accuracy of a neural fuzzy network on the number of learning epochs for classical and modified Kwan and Cai neurons.

**6. Example of modeling of industrial and technological process in a complex system**

Currently, enterprises are trying to extend the safe operation of their equipment. Using this approach allows you to increase the overhaul intervals, to plan diagnostics, with minimal economic losses. This is achieved by transferring equipment to milder operating conditions, adjusting, if possible, production-technical and information-analytical processes occurring in the system, using additional control and measuring devices, introducing additional stages of raw materials analysis, etc. Control and measuring devices allow obtaining more than a hundred parameters per second. This allows you to improve the quality of control of the processes occurring in the system.
Information that enters the system may arrive with an error, with a time delay, or not at all [8]. There is also information that is only valuable at this point of time [7]. The value of information decreases over time. The ability to quickly and efficiently process such information is one of the criteria for the effective operation of the system.

With an increase in the amount of information from heterogeneous sources, as well as the complexity and intensity of information flows, the need for high-quality and operational analysis and management of information-analytical processes increases.

Due to the constantly changing conditions of the external environment, the change and adjustment of the processes taking place in the system, the use of standard approaches to the processing and analysis of such information is currently economically impractical.

Thanks to the development of computer technology, the use of neuro-fuzzy components in systems is not expensive. Neuro-fuzzy components have proven themselves well when used in the medical field, in robotics, in autopilot systems, etc.

The use of neuro-fuzzy components improves the quality of analysis and process control. The neuro-fuzzy component allows in the shortest possible time to adjust to changes in production, technical and information-analytical processes, environmental factors.

Let’s consider the control scheme of the oil refining process (Fig. 4).

The operating process of an oil refinery is largely dependent on the type of oil that is supplied. Oil is made up of a wide variety of hydrocarbons. Their molecules differ in mass, which, in turn, is determined by the number of carbon and hydrogen atoms that make up them. To obtain this or that petroleum product, substances with very specific characteristics are needed. Each batch of oil that enters the refinery is different in its chemical composition.

The existing scheme of the industrial and technological process consists of two main parts:

• Technological equipment (lower part of the figure) on which the technological process of oil refining takes place. The incoming raw materials are treated through a desalting unit, then heated and fed to the atmospheric distillation unit for separating oil into fractions, by repeated evaporation and condensation of vapors, carried out at normal (atmospheric) pressure. After that, each fraction is processed in accordance with its own industrial and technological process.

• Control system (upper part of the figure), which consists of a block for filtering input data, as well as blocks for automatic and manual process control. In this diagram, a model of the system is introduced into the control loop (including a model of industrial and technological processes in the system closely interacting through the data bus and a corresponding model of information-analytical processes used to analyze and control the system). The scheme also includes a control decision support system connected to the model outputs and forming decision options for the operator.

The model of industrial and technological and information-analytical processes based on neuro-fuzzy Petri net can be represented as follows (Fig. 5).
Figure 4. Scheme of the industrial and technological process of oil refining.
Figure 5. Model of industrial and technological and information-analytical processes based on neuro-fuzzy Petri net.

Neuro-fuzzy Petri net can be represented as follows:

\[ NPN = (P, T, I, O, A, PR, FP, f, \alpha, m_0, n, \mu) \]

where:
- \( P = \{p_1, p_2, \ldots, p_n\} \) is a finite non-empty set of Petri net positions;
- \( T = \{t_1, t_2, \ldots, t_m\} \) is a finite non-empty set of Petri net transitions;
- \( I, O, A, PR, FP, f, \alpha, m_0, n, \mu \) are functions related to the Petri net.
- O - output function of transitions;
- A is a finite set of arcs;
- PR is a finite set of priorities that determine the order of firing transitions in the case of several active transitions;
- FP - a function that assigns the FT triggering priority to each transition: T -> PR;
- f = {f1, f2, ..., fn} is the vector of values of the fuzzy transition function;
- α = {α1, α2, ..., αn} is the vector of transition firing values;
- m0 is the vector of the initial marking, each component of which is determined by the value of the membership function of the fuzzy presence of one marker in the corresponding position. Where are all the possible markings of the network
- \( M \cong \{m: m: P \rightarrow (U \cup \{\emptyset\}) \times R\};
- n = \{n1, n2, ..., pm\} - a finite set of integer values of labels, which is necessary for the transition to be triggered;
- \( \mu = (\mu_1, \mu_2, ..., \mu_n) \) is the vector of network marking.

7. Specialized software

Specialized software has been developed within which it is possible to simulate industrial and technological processes and implement information-analytical processes of a complex system with the following capabilities:
- formation of an ontological model of a complex system, including classes of information entities and quasi-hierarchical connections between them;
- input and storage of user data and data obtained from external sources;
- using a neural network supervisor to validate external and analytical data;
- building an information-analytical process using the mechanisms of constructors based on neuro-fuzzy Petri nets;
- flexible adjustment of priority management of information-analytical processes competing for resources based on the apparatus of neuro-fuzzy Petri nets.

Figure 6. Screen form of specialized software for modeling industrial and technological processes.
8. Conclusion

For effective functioning within the framework of a complex system, industrial and technological processes are supported by appropriate information-analytical process-es that ensure the collection and analysis of information, as well as modeling and making control decisions for the industrial and technological process.

A variety of neuro-fuzzy Petri nets with temporal fuzzy neurons is proposed.

An example of constructing a model of an industrial and technological process and the corresponding information-analytical processes is considered.

The developed specialized software for modeling industrial and technological processes and the implementation of information-analytical processes is considered.

9. References

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