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ABSTRACT

of the dissertation for the degree of Doctor of Sciences

MODELING OF INTELLIGENT CONTROL SYSTEMS USING EXTENDED PETRI NETS

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GENERAL DESCRIPTION OF THE DISSERTATION

Relevance of the topic and the degree of processing. Currently, in accordance with the directions of development of the modern information society, methods and means of creating mathematical, algorithmic and software for intelligent control systems (ICS) are being actively developed. ICS are designed for control and analysis of complex dynamic systems (DS) with support for fuzzy logic, decision making and forecasting in the presence of fuzzy, stochastic, inaccurate nature of uncertainties in the simulated objects.

Complex DS include production, meteorological, transport, technological, organizational, sociological and other systems that operate under varying degrees of resource and information limitations. When creating an ICS for complex DS, a significant place is played by the development of mathematical methods, algorithms and modeling software based on modern theories. Means for describing logical, qualitative, quantitative and system dependencies are important components of modeling control objects (CO).

ICS are distinguished by the use of artificial intelligence theory methods and decisions are made on the basis of expert knowledge. The MIS includes modeling subsystems of various types: logical inference models, imitation models (IM), decision-making models, neural network models, analytical models, models for selecting the best options, production models, etc. Issues of modeling complex DS and including ICS Many scientists have been involved in and devoted their scientific work, the names of some of them are listed below: Zade L.A., Mamdani E., Aliyev R.A., Pospelov D.A., Pospelov G.S., Larichev O.I., Pegat A., Levinson S.K., Jensen K., Christensen L.M., Ahmedov M.A., Mustafaev V.A., Zaitsev D.A., Rybina G.V., Kayd H., Nabi H.Z., Nilsson N.J., Jiang J.K. and etc.

The study of the behavior of processes and patterns of functioning of complex DS in uncertain situations, the development and improvement of methods, algorithmic and software modeling when creating an ICS are relevant, since reliability, predictability, modifiability in the design and operation of complex DS are necessary properties leading to the elimination of emergency situations and increased productivity. Issues of creating an ICS are a priority area of research for the world's leading scientific organizations: International Federation of Accountants - IFAC, Institute of Electrical and Electronics Engineers - IEEE, Association for Computing Machinery - ACM and the applications of this area find the most numerous areas of application in science and production, which confirms the relevance of the task.

DS consist of components that, depending on the situation of the system, are in a certain state and, when making a transition from one state to another state, the system functions according to some specific conditions, which corresponds to the fundamental structure of Petri nets (PN). The joint venture has the ability to modify and analyze the developed models. Based on the listed properties for the management, monitoring and analysis of complex DS, various extended and combined-extended modifications of the formal PN apparatus were selected for simulation in the development of ICS of complex DS.

To develop an ICS for complex DS, modifications of the PN require the representation of sequences of phenomena, parallelism of events, types and dynamics of resources, the relationship of constituent elements, the uncertain nature of the operating environment of individual elements and the system as a whole. As a result of the research, it was revealed that there are some modern software and tools for constructing complex DS based on ordinary and some expanded PN (Petri netvork, AT-Technology, PIPE, RTXPS, Rdo, TiPeNeSS, DCNET, RTworks, etc.), which take into account the display of some of the above factors separately, which is why they do not sufficiently represent modern trends and do not have a more integrated and comprehensive approach to solve the problem. For the above reasons, modern means of constructing ICS of complex DS do not satisfy and do not meet today's requirements and there is a need for research.

The relevance is also due to the fact that when designing a DS there is a high risk of errors. The manifestations of these errors show themselves to be emergency, dead-end situations during operation, and all this comes at a very high price. The traditional approach - analytical methods of system analysis, described by different types (differential, integral, nonlinear, etc.) of equations, is not entirely applicable and difficult to solve due to the high complexity of the DS. For these reasons, currently, due to the high development of computer systems and technologies, there is a strong interest in the approach of modeling complex DS using IM on PN, enriched with elements of artificial intelligence (AI).

Many works are devoted to the problems of development, analysis and synthesis of IMs on various extended PN. In the dissertation work, with the aim of creating an ICS for complex DS, a mathematical apparatus based on combined, integrated modifications of extended PN is proposed as a basic method. When modeling the ICS of complex DS, it is often necessary to describe discrete processes in parallel with continuous ones, process both clear and fuzzy parameters, which leads to hybridization due to the integration of modified designs of extended PN and AI methods. This approach compensates for the shortcomings of both modern AI methods and PN modeling methods, which serves to bring closer to the more real nature of processes and natural intelligence.

Preliminary analysis showed that integrated modifications of PN using colored, fuzzy, stochastic structures are a promising basis for the development of ICS for complex DS, which confirms the relevance of the topic of the dissertation work.

Object and subject of research. The object of the study is ICS models of complex DS operating in an uncertain environment, developed using various modifications of extended PN. The subject of the research is the improvement and development of methods, algorithmic and software for modeling ICS of complex DS based on extended modifications of colored, fuzzy, stochastic PN and their integrated variants.

The goals and objectives of the study. The purpose of the dissertation research is to improve existing and develop new methods, algorithmic and software tools, for constructing ICS of complex DS, based on colored, fuzzy, stochastic extended modifications of SP and their integrated variants.

To achieve this goal, the following scientific and practical tasks were completed in the dissertation work:

1. Review of literature sources on the development of research and development in the field of ICS, on the use of AI elements in complex DS, on determining the role of simulation modeling in the creation of ICS of complex DS and the modeling capabilities of the mathematical apparatus for imitation of various types of extended PNs, analysis of the applicability of combined and integrated modifications colored, fuzzy, stochastic SPs for developing ICS models of complex DS;
2. Development of approaches and methods for creating an IM for the functioning of complex DS using the mathematical apparatus of simulation of extended PN with the ability to represent and operate with uncertain information of an inaccurate, fuzzy and stochastic nature;
3. Development of mathematical and algorithmic support for the functioning of the proposed extended modifications of SP types: generalized colored Petri nets (CPN); combined modifications of fuzzy Petri nets (FPN) and stochastic Petri nets (SPN); integrated fuzzy colored Petri nets (FCPN) and colored stochastic Petri nets (CSPN);
4. Development of management models based on a generalized CPN, combined modifications of expanded FPN, SPN and integrated FCPN, CSPN.
5. Presentation of a hybrid approach to modeling automated intelligent control using the integrated FCPN imitation apparatus, the fuzzy logical inference method and software and tool modeling systems CPN Tools and MATLAB;
6. Construction of visual-imitation graph-models of intelligent complex DS using combined and integrated extended PN;
7. Software implementation of the developed algorithms based on the proposed methods in the CPN ML language in terms of their addition to the standard software of the system;
8. Experimental computer simulation and verification of developed control models for complex DS using the CPN Tools

application and analysis using the properties of PN analysis;

9. Development of a method for converting FA (into PN for the analysis and synthesis of complex DS, certain subsystems of which are modeled using FA, based on mapping tables of transitions and outputs of FA into matrices of input and output incidents of PN. Automation of the developed method and verification of the results obtained based on the topology of converting the FA into the PN.

Research Methods. To solve the problems, computer modeling methods, heuristic methods, methods for constructing membership functions, simulation modeling methods, matrix theory methods, fuzzy logical inference methods, computer graphics and visualization methods, also the theory of fuzzy sets, the theory of PNs and their modifications, the theory of finite state machines were used, methods for constructing algorithms, methods for developing and testing software, methods for simulation and model verification.

The main tasks to be defended. The following points are put forward for defense in the dissertation:

1. Formal mathematical representation of complex dynamic intelligent systems (DIS) and ICS;
2. Mathematical formalizations and algorithmic support for the functioning of generalized CPPs and combined modifications of extended FPNs and SPNs;
3. Integrated modifications of extended FCPN and CSPN, respectively, having the advantages of expanded modifications of CPN, FPN and SPN;
4. Models based on generalized, combined and integrated modifications of extended CPN, FPN and SPN, automation models of adaptive fuzzy control using integrated FCPN;
5. Hybrid methodology for modeling automated intelligent control based on an integrated extended FCPN and a model of fuzzy control of the speed of a water pump using the presented hybrid modeling;
6. Software implementation of the developed algorithms in the CPN ML language as an addition to the CPN Tools system software;
7. Methodology for constructing imitation-visual graph-

models of complex DS on CPN Tools using the developed types of combined and integrated modifications of extended PN;

8. Results of simulation and verification of the developed models using the CPN Tools application and analysis of the developed models of complex DS on combined and integrated PN, using the properties of PN analysis;

9. Methodology for converting a FA into a PN based on matrix theory, an algorithm and software implementation for automating the conversion of tables of transitions and outputs of a FA into a matrix of input and output incidents of a PN simulating a FA in the C++ programming system.

The scientific novelty of the study. The scientific novelty of the research is as follows:

1. The characteristic features of complex DS that require intelligent control and the requirements for modern control systems have been identified and systematized, formal mathematical representations of DIS and ICS have been developed. The purpose, areas of application, types and trends in the use of various methods of simulation modeling in the development of ICS have been studied;

2. The choice of extended PNs in the role of the basic mathematical formalism in modeling the ICS of complex DS is justified on the basis of certain properties and capabilities identified by summarizing forty years of world experience in creating extended PNs. The identified advantages and disadvantages of the most common classes of extended PNs are systematized, on the basis of which the direction of development of extended modifications of PNs is determined, corresponding to modern requirements of the theory of system modeling - generalization, combination and integration of extended modifications of PNs;

3. An algorithm for the functioning of generalized CPNs has been developed, representing the main stages of the mathematical formalization of the combination of two concepts - degenerative and selective CPNs, on the basis of which a control model for the machining center module in the Flexible production system (FPS) has been developed, the advantages of generalized CPNs have been confirmed in comparison with the basic configurations;

4. A model has been developed for determining the stability “as a whole” of an evolutionary fuzzy controller using CPN in the CPN Tools system, which makes it possible to analyze the sequence of functioning of the blocks of an evolutionary fuzzy controller before returning to the initial state, which is considered a significant task in design;

5. A combined modification of three types of FPP has been developed, where transitions are assigned membership functions of fuzzy triggering and a fuzzy triggering threshold, and a type where positions are assigned membership functions of the presence of one marker in the corresponding position of a given network, which has the advantages of all three types. The correspondence of the modification to the modeling of fuzzy production rules is shown. The control system of the production module was modeled using the presented combined FPN.

6. A combined modification of the SPN and an algorithm for its functioning have been developed, an integrated CSPN based on the CPN and a combined SPN has been presented for the convenience of solving specific problems of modeling complex DS with probabilistic properties that expand the modeling capabilities relative to the basic SPN. It is substantiated that CSPN provide a more transparent interpretation of the dynamics of marks in the SPN and a better analysis of the modeling process;

7. An integrated modification of FCPN has been developed, obtained by integrating extended FPN and CPN, in which the membership functions of terms of a linguistic variable are assigned to markers in the role of color, fuzzy conditions of existence are inserted into arcs, the advantages of which are demonstrated on the developed automation model of adaptive fuzzy control of the process of turning on and off water pumps according to the water levels in the pump well. It has been proven that the presented FCPN narrows the model space and has a wider range of modeling objects, in contrast to the basic FPN and CPN.

8. An original hybrid methodology for automated intelligent control based on an integrated extended FCPN has been developed, the structure and content of hybridization and supporting software

and tool systems have been determined. Using the presented hybrid modeling, a model of fuzzy control of the speed of a water pump has been developed, which provides more accurate and smooth adjustment of rotation within load limits according to water consumption modes, compared to other known models.

9. A methodology has been developed for converting a FA into a PN based on converting the tables of transitions and outputs of the FA into a matrix of input and output incidents of a PN. Theorems representing formulas for compiling elements of the incidence matrices of the PN of a imitating FA have been put forward and proven. An algorithm for automating the conversion of FA into a PN has been developed, on the basis of which the construction of a PN converted from a given model in the form of a FA has been carried out. A software module has been developed for the algorithm for converting FA into PN in the C++ programming system.

Theoretical and practical significance of the research. The theoretical and practical significance of the results obtained lies in the creation of approaches and modeling methods based on generalized, combined and integrated modifications of extended PN, algorithmic and software for the functioning of the IM developed on the basis of the proposed modifications, focused on the use of complex DS in the creation of ICS. The developed tools make it possible to deeply and more smoothly display the properties of a modeling object, bring formal models closer to real ones, simplify the modeling process and make models more compact. The results obtained make it possible to expand the capabilities of the CPN Tools system and modern computer simulation systems based on PN in general. The practical significance of the research is also determined by the effective applicability of the developed mathematical, algorithmic and software in the creation of ICS for complex DS, such as gas FPS, pumping stations, electric power systems, and the design of complex discrete devices.

The reliability of scientific results is confirmed by methodological rigor from the standpoint of systems theory, substantiation of statements, theoretical calculations, computer simulations of developed IMs, analysis of the obtained data from computer experiments, application of fundamental principles of computer modeling, graphical representations of the calculated values of membership functions and the results of logical inference, mathematical proof of theorems and comparison of the obtained simulation data with data existing in the scientific literature.

The methodology and technology for developing generalized, integrated and hybrid models presented in the dissertation are original and allow us to reduce and reduce the complexity of practical problems, select more adequate types of methods relevant to the properties of the studied CO, synthesizing and interpreting extended modifications of the PN to solve problems caused by distortions and limitations of traditional modeling methods.

Approbation and implementation of the results. The main results of the dissertation were discussed at the following national and international scientific and technical conferences:

1. The 5th International Conference on control and optimization with industrial applications. COIA. (Baku, august 27 – 29, 2015);
2. Международная научно–техническая конференция «Интеллектуальные технологии в машиностроении». (Baku, 28 – 30 сентября, 2016);
3. Республиканская научная конференция «Задачи прикладной математики и новые информационные технологии», (Сумгаит, 15 – 16 декабря, 2016);
4. Международная научная конференция «Теоретические и прикладные проблемы математики», (Сумгаит, 25 – 26 мая, 2017);
5. Международная научно–техническая конференция «Наука, технология, производство – 2017. Прикладная наука как инструмент развития нефтехимических производств», (Уфа, 22 мая, 2017);
6. XXXI International Conference "Problems of Decision Making Under Uncertainties – PDMU", (Lankaran, july 3 – 8, 2018);
7. Международная научная конференция «Информационные системы и технологии. Достижения и

перспективы», (Сумгаит, 15 – 16 ноября, 2018);

8. International Conference "Modern Problems of Innovative Technologies in Oil and Gas Production and Applied Mathematics", (Baku, december 13 – 14, 2018);

9. II Всероссийская научная конференция с международным участием: «Информационные технологии в моделировании и управлении: подходы, методы, решения», (Тольятти, 22 – 24 апреля, 2019);

10. V Международная Научно–практическая очно–заочная конференция «Проблемы и перспективы внедрения инновационных телекоммуникационных технологий», (Оренбург, 22 марта, 2019);

11. XXXII Международная научная конференция «Математические методы в технике и технологиях – ММТТ», (Санкт Петербург, 3 – 7 июня, 2019);

12. Республиканская научная конференция «Актуальные проблемы математики и механики», (Баку, 2 – 3 мая, 2019);

13. XIII Международная конференция «Фундаментальные и прикладные проблемы математики и информатики», (Махачкала, 16 – 20 сентября, 2019);

14. Сборник трудов Международной научно–технической конференции «IT–технологии: развитие и приложения», (Владикавказ, 12 – 13 декабря, 2019);

15. “Azərbaycan və Türkiyə Universitetləri: təhsil, elm, texnologiya" I Beynəlxalq elmi–praktiki konfransı, (Bakı, 18 – 20 dekabr, 2019);

16. Международная научно – практическая очно – заочная конференция «Проблемы и перспективы внедрения инновационных телекоммуникационных технологий», (Оренбург, 20 марта, 2020);

17. Республиканская научная конференция «Фундаментальные проблемы математики и применение интеллектуальных технологий в образовании», (Сумгаит, 23 – 24 апреля, 2020);

18. Международная научная конференция «Информационные системы и технологии. Достижения и

перспективы», (Сумгаит, 09 –10 июля, 2020).

19. 7th International Conference on Control and Optimization with Industrial Applications (COIA–2020), (Baku, august 26 – 28, 2020);

20. 2nd International Scientific–Practical Conference dedicated to the 100th anniversary of ASOIU "Modern information, measurement and control systems: problems and perspectives, MIMCS'2020", (Baku, november 05 – 06, 2020);

21. XV International Conference "Measurement and control in complex systems (MCCS)", (Vinnytsia: VNTU, october 8 – 10, 2020);

22. V All-Ukrainian Scientific and Practical Conference "Energy Efficiency: Science, Technology, Energy", (Kyiv, november 25, 2020);

23. VI Международная научно-практическая конференция молодых ученых: «Прикладная математика и информатика: современные исследования в области естественных и технических наук», (Тольятти, 20-22 апреля, – 2021);

24. XIV Международная конференция «Фундаментальные и прикладные проблемы математики и информатики», (Махачкала, 16–19 сентября 2021);

25. Республиканская научная конференция «Задачи прикладной математики и новые информационные технологии», (Сумгаит, 09 – 10 декабря, – 2021).

26. 8th International Conference on Control and Optimization with Industrial Applications (COIA-2022), (Baku, 24 – 26 August, – 2022);

27. Республиканская научная конференция «Прикладные задачи математики и новые информационные технологий», (Сумгаит, 15 – 16 декабря, – 2022).

The name of the organization in which the dissertation was completed. The dissertation work was performed at the Department of "Informatics" of Sumgait State University.

Volume and structure of the dissertation. The dissertation consists of introduction, five chapters, conclusion, list of references and applications. The main content of the work consists of 275 pages, 40 figures. The bibliography lists 201 sources. The volume of general and structural sections of the dissertation is approximately distributed as follows:

- ✓ Total - 380000 characters;
- ✓ Introduction - 19800 characters;
- ✓ Chapter One - 81000 characters;
- ✓ Second chapter - 63000 characters;
- ✓ Chapter Three - 87000 characters;
- ✓ Chapter Four - 74000 characters;
- ✓ Chapter Five - 52000 characters;
- ✓ Conclusions - 4900 characters.

THE CONTENT OF THE DISSERTATION

The introduction substantiates the relevance of the dissertation, defines the purpose and directions of research, identifies the main problems that need to be addressed, The theoretical and practical significance of the results, gives basic provisions for protection, demonstrates scientific innovations and the practical significance of the results.

The first chapter examines the current state and development paths of ICS, the characteristic features of complex DS and approaches to their modeling, based on literature sources. The role of simulation modeling in the creation of ICS, the properties of general purpose and engineering and scientific applications of IM are determined. The requirements for the use of IM in modeling the ICS of complex DS have been identified, the properties and trends in the development of the theory of PN and extended modifications have been determined, which provide the basis for considering the PN in the role of a basic formalism in the development of an ICS. An analysis of modern software tool systems built on the basis of PN theory has been carried out, and the choice of a basic software tool system corresponding to research and development in the field of ICS has been justified.

Based on the analysis of studies of literary sources in order to determine the current state of the ICS, modeling complex DS, approaches to modeling the ICS using extended PNs, the following were identified:

– There is a significant difference between action and perception, between reasoning and mathematical operations, between present real and laboratory behavior of the CO. The real behavior of complex DS is not yet entirely close to the constructed computer prototypes, and the increase in modeling efficiency is determined by the use of modern AI trends, through which the ICS will be ready to inform about the behavior of the op CO only based on the analysis of the generated data, but also on the basis of experimental thinking design and logical inference. There is no unified approach to the mathematical formalization of ICS;

– The classical theory of system modeling is not able to make final decisions corresponding to the uncertainty factors of a fuzzy, stochastic, inaccurate type, which must be taken into account when developing modern algorithmic and software ICS. Under conditions of complexity of the modeling object and the impossibility of its adequate analytical description or the possibility of representation by mathematical equations that do not have a solution, it is advisable to turn to IM. A competent choice of IM determines the adequacy and quality of modeling;

– Characteristic features - compatibility of functional and structural modeling, visualization of processes, expressiveness of logical dependencies, decomposition and complex analysis capabilities make it possible to choose the PN simulation modeling apparatus as the main basic mathematical formalism for studying complex DS. Expanded modifications of PN and their generalized, combined, integrated options lead to the development of more compact, visually accessible, mathematically analyzed, close to real op-amp models.

– It is rational to develop approaches to using PN to effectively solve problems of modeling systems that require the inclusion of AI elements, but in most cases, when solving such problems using PN, additional actions are required, which leads to an increase in the number of transitions and network positions and, consequently, to the construction of cumbersome models. The way out is to develop various modifications of the PN with expanded capabilities.

– CPN, SPN, FPN – the more common extensions have the ability to describe the functional properties of the CO and are based on the introduction, respectively, of stochastic, fuzzy, time parameters on the structural elements of ordinary PN and on the means of changing the interpretation of the functions performed by network transitions. Existing advanced SPs having peculiar advantages still face difficulties to interpret the heuristic cognition of experts and the features of various complex CO;

– Generalized, combined and integrated models combine the capabilities of different types of extended classes of PN models, with the aim of having significantly greater descriptive, functional properties and analysis methods. In addition, integrated PNs provide the highest visual expressiveness of models and the ability to process uncertain data to identify functional, structural patterns of the system and for data exchange in the ICS;

– Mastery of the high capabilities of visual expressiveness, methods of analysis and verification of models, the open principle of introducing software modules to individual structural elements to solve different types of problems and to expand the capabilities of the theory of PN modeling itself provide the basis for accepting the software and tool computer system CPN Tools as an important factor for further research when developing an ICS for complex DS with the introduction of software modules that operate with qualitative parameters based on the developed mathematical and algorithmic software.

The analysis of literary sources on the topic showed that there are a number of unsolved problems of theoretical and practical interest, on the basis of which the objectives of the dissertation work were determined.

The second chapter is devoted to modeling issues using CPN. An algorithm for the functioning of generalized CPNs has been developed. A control model for a machining module in a flexible manufacturing system using a generalized CPN has been developed. A model has been developed to analyze the stability of an evolutionary fuzzy controller using CPN in the CPN Tools system.

It has been determined that the modern theory of CPN uses data types in programming languages and the color itself can be formed as a type[1]. A model on the CPN is usually created at the initial stages of design, and then gradually refined until a more detailed and correct description of the simulated CO is obtained. This property helps to reduce the existing differences between reasoning

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[1] Jensen, K., Kristensen, L.M. Colored Petri Nets: A Graphical Language for Formal Modeling and Validation of Concurrent Systems // Communications of the ACM, – 2015, v. 58(6), – p. 61-70.

and algorithmic operations, between real behaviors and computer prototypes of CO, and opens up a wide range of applications for CPN, including reconfigurable systems.

It has been revealed that in all its advantages, both in theoretical and practical aspects, not all issues have been resolved; in the existing two separate types of CPN - degenerative and selective, the modeling capabilities are limited to some extent, especially when branching processes and when analyzing color achievability, in order to overcome which presents a generalized modification of the CPN[2].

A generalized RSP is formally defined as a set of types:

$$N_{GCPN} = (P, T, F, H, \Omega, \lambda, \varphi, \psi, \mu_0)$$

Where:

- P and T – are respectively finite sets of positions and transitions:

$$P = \{p_1, p_2, p_3, \ldots\}, T = \{t_1, t_2, t_3, \ldots\}$$

- F and H – are respectively the functions of incidence of sets of positions and transitions:

$$F : P \times T \to \{0, 1, 2, \ldots\}$$

$$H : T \times P \to \{0, 1, 2, \ldots\}$$

- Ω – non-empty finite set of colors of positions and markers:

$$\Omega = \{\omega_1, \omega_2, \omega_3, \ldots\}$$

- λ – color distribution function across network positions:

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[2] Мустафаев, В.А., Гусейнзаде, Ш.С. Разработка модели управления обрабатывающего центра с применением раскрашенных сетей Петри // – Москва: Вестник компьютерных и информационных технологий, – 2018. – №3(165), – с. 36-44.

$$\lambda : P \times \Omega \to \{0,1\}$$

- φ – function of distribution of colors of markers across input positions of network transitions:

$$\varphi : (P \times \Omega) \times T \to \{0,1,2,\ldots\}$$

- ψ – function of distributing marker colors among output positions of network transitions:

$$\psi : T \times (P \times \Omega) \to \{0,1,2,\ldots\}$$

- μ_0 – initial distribution of markers by position:

$$\mu_0 : P \times \Omega \to \{0,1,2,\ldots\}$$

Functions φ and ψ define the laws of transition firing and determine the distribution of marker colors among network positions.

The marking of network positions is represented as a matrix of dimension $|P| \times |\Omega|$, the elements of which are composed of the numbers of color markers ω in position p.

Algorithm for the functioning of generalized CPN:

The beginning of the algorithm.

Step 1. Step 1. Creating a matrix of input incidents $F = [f_{ij}]$, where $i = \overline{1,n}$, $j = \overline{1,m}$ (n-number of positions, m-number of transitions). Element f_{ij} is equal to the number of arcs from the i-th position to the j-th transition:

$$f_{ij} = \begin{cases} 1, & if \quad p_i \in {}^{\bullet}t_j \ ; \\ 0, & \text{else.} \end{cases}$$

Шаг 2. Creating a matrix of output incidents $H = [h_{ji}]$, where $i = \overline{1,n}$, $j = \overline{1,m}$. Element h_{ji} is equal to the number of arcs from the j-th transition to the i-th position:

$$h_{ji} = \begin{cases} 1, & if \quad p_i \in t_j^{\bullet}\ ; \\ 0, & \text{else.} \end{cases}$$

Step 3. Creating the Initial Labeling Matrix $\mu = [\mu_{il}]$, где $i = \overline{1,n}$, $l = \overline{1,k}$ (k- the number of colors). k is). The μ_{il}element is equal to the number of color markers ω_l at p_i.

Step 4. Creating a color distribution matrix by position $\lambda = [\lambda_{il}]$, where $i = \overline{1,n}$, $l = \overline{1,k}$:

$$\lambda_{il} = \begin{cases} 1, & if \quad p_i \times \omega_l \in \Omega; \\ 0, & else. \end{cases}$$

Step 5. Creating a matrix of marker color distribution across input transition positions $\varphi = [\varphi_{jl}]$, ($j = \overline{1,m}$, $l = \overline{1,k}$):

$$\varphi_{jl} = \begin{cases} 1, & if \quad \left(\overrightarrow{{}^{\bullet}t_j \times \omega_l}\right) \in {}^{\bullet}C_t; \\ 0, & \text{else.} \end{cases}$$

Step 6. Creating a matrix of marker color distribution across output transition positions $\Psi = [\Psi_{jl}]$,($j = \overline{1,m}$, $l = \overline{1,k}$):

$$\psi_{jl} = \begin{cases} 1, & if \quad \left(\overrightarrow{t_j^{\bullet} \times \omega_l}\right) \in C_t^{\bullet}; \\ 0, & else. \end{cases}$$

Step 7. Search for an allowed transition. For each transition t_j, $j = \overline{1,m}$ the triggering condition is checked:

7.1. From the matrix $F = [f_{ij}]$ all output positionsp_{i_1}, $p_{i_2}, \dots, p_{i_z}$ of transition t_j are determined, where $z = \left|{}^{\bullet}t_j\right|$

7.2. From the matrix φ all available color distributions across output positions are determined t_j: ω_{l_1}, $\omega_{l_2}, \dots, \omega_{l_r}$, $r \in [1, k]$;

7.3. From the matrix μ numbers of a certain marker color are selected in all available transition output positions t_j:

$$\mu_{i_z l_r} = \left(p_{i_z}, \omega_{l_r}\right), \qquad z = \overline{1, \left|{}^{\bullet}t_j\right|}, r = \overline{1,k};$$

If for $\forall\ i_z$ there $\exists\ l_r$ such that, $\mu_{i_z l_r} \geq f_{i_z j}$, then transition t_j s allowed and the transition to step is performed.

Step 8. If the triggering condition for a transition is not met, then index j is increased by one: $j = j + 1$. If $j \leq m$ then the transition to paragraph 7.1 is carried out, otherwise a deadlock state is reported and the transition to the end of the algorithm is carried out.

Step 9. Calculating Matrix Elements μ':

$$\mu_{il}' = \mu_{il} + \varphi_{jl} * f_{ij} - \psi_{jl} * h_{ji}$$

где $i = \overline{1,n}$; $j = \overline{1,m}$; $l = \overline{1,k}$;

Step 10. At the user's choice, the process is completed (go to the end of the algorithm) or continue until the desired marking is obtained (go to step 7).

End of the algorithm.

Control model of a machining module in a flexible production system (FPS) using a generalized CPN. A typical machining center is considered, consisting of one industrial robot, one personal input drive, two similar devices for performing the same operation on different workpieces of the same type, and one personal output drive. The module communicates with the previous and subsequent modules accordingly using the above drives. The module processes one type of part. The blanks arrive at the personal input storage and await processing. Free device1 or device2 picks up the workpiece from the input hopper. If both devices are free, then a conflict situation appears between them. The conflict is resolved by randomly selecting one device and partially paralleling it, alternating them. The processed parts arrive at the output storage and await sending to the next module.

Possible states of the module are described by positions: P_1 – the robot is free; P_2 – there are workpieces in the input storage; P_3 – the robot has grabbed the workpiece; P_4 – device1 is free; P_5 – device2 is free; P_6 – the workpiece is in the working area of device1;

P_7 – the workpiece is in the working area of device 2; P_8 – device 1 processes the workpiece; P_9 – device 2 processes the workpiece; P_{10} – in device 1 the workpiece is processed; P_{11} – in device 2 the workpiece is processed; P_{12} − the robot grabbed the processed part; P_{13} – the part is in the output storage.

Possible events are described by transitions: t_1 − the robot grabs the workpiece from the input storage; t_2 – the robot inserts the workpiece into device1; t_3 – the robot inserts the workpiece into device2; t_4 – processing of the workpiece in device 1 begins; t_5 – processing of the workpiece in device 2 begins; t_6 – processing of the workpiece in device 1 ends; t_7 –processing of the workpiece in device 2 ends; t_8 − the robot grabs the part from device1; t_9 − the robot grabs the part from device2; t_{10} − the robot inserts the part into the output storage.

Using “If-Then” logic, the relationships between events and states are described by products:

if p_1 and p_2 then t_1;
if t_1 then p_3;
if p_3 and p_4 then t_2;
if p_3 and p_5 then t_3;
if t_2 then p_1 and p_6;
if t_3 then p_1 and p_7;
if p_6 then t_4;
if p_7 then t_5;
if t_4 then p_8;
if t_5 then p_9;
if p_8 then t_6;
if p_9 then t_7;
if t_6 then p_4 and p_{10};
if t_7 then p_5 and p_{11};
if p_{10} and p_1 then t_8;
if p_{11} and p_1 then t_9;
if t_8 then p_{12};
if t_9 then p_{12};
if p_{12} then t_{10};
if t_{10} then p_1 and p_{13}.

The incidence function of a set of positions is represented by the matrix $F(13,10)$:

$$F(13,10)=\begin{vmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0\\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{vmatrix}$$

The incidence function of a set of transitions is represented by the matrix $H(10,13)$:

$$H(10,13)=\begin{vmatrix}
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{vmatrix}$$

The distribution of marker colors over the input and output positions of transitions is represented by matrices:

$$\varphi(10,5)=\begin{vmatrix}1&0&0&1&0\\0&1&0&1&0\\0&0&1&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&0&1\\0&0&0&0&1\\0&0&0&0&1\end{vmatrix}\qquad \psi(10,5)=\begin{vmatrix}0&0&0&1&0\\1&0&0&1&0\\1&0&0&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&0&1\\0&0&0&0&1\\0&0&0&0&1\\0&0&0&0&1\\1&0&0&0&1\end{vmatrix}$$

The presented model of generalized RSP uses the following descriptions of the set of colors and variables:

– Many colors of markers: C = {r (robot), u1 (device 1), u2 (device 2), z (workpiece), d (part)};

– Many colors of positions: w1 (with the resolution of placing color markers r (robot)); w2 (with the resolution of placing color markers u1 (device1)); w3 (with the resolution of placing color markers u2 (device 2)); w4 (with permission to place markers of color z (blank)); w5 (with permission to place markers of color d (detail));

– Many colors of arcs: x1 (with permission to move color markers r); x2 (with permission to move color markers u1); x3 (with permission to move color markers u2); x4 (with permission to move color markers z); x5 (with permission to move color markers d).

– The distribution of colors over network positions and the initial marking are represented by the matrices λ(13,5) and $\mu_0(13,5)$:

$$\lambda(13,5)=\begin{vmatrix}1&0&0&0&0\\0&0&0&1&0\\0&0&0&1&0\\0&1&0&0&0\\0&0&1&0&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&1&0\\0&0&0&0&1\\0&0&0&0&1\\0&0&0&0&1\\0&0&0&0&1\end{vmatrix}\quad \mu_0(13,5)=\begin{vmatrix}1&0&0&0&0\\0&0&0&2&0\\0&0&0&0&0\\0&1&0&0&0\\0&0&1&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\end{vmatrix}$$

Software implementation, visualization (Figure 1) and analysis of the model were performed using the CPN Tools tool system. Based on the above initial data, computer experiments of network simulation were carried out; by eliminating design errors and design defects, an optimal trajectory was selected that ignored random delays during model simulation. In the initial marking, one transition t_1 is allowed (the robot picks up the workpiece from the input accumulator), which is marked. In the second step, transitions t_2 and t_3 conflict. In this case, the conflict is resolved not by priority, but by a random choice of transition t_2 or t_3. The semantics of executing parallel events is interleaving.

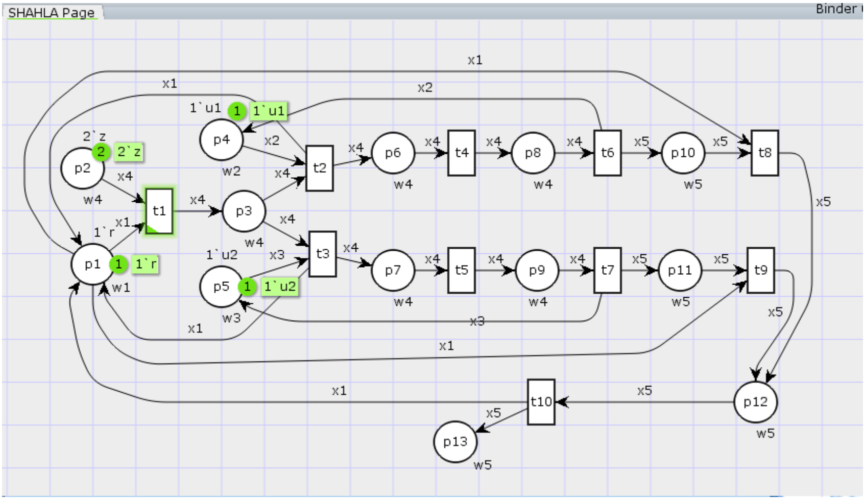

Figure 1. Graph model of the CPN module of the FMS module

At the 1st and 2nd steps of the simulation, marking matrices were obtained $\mu_1(13{,}5)$ и $\mu_2(13{,}5)$:

$$\Rightarrow t_1 \Rightarrow \mu_1(13{,}5)=\begin{vmatrix} 0&0&0&0&0\\ 0&0&0&1&0\\ 0&0&0&1&0\\ 0&1&0&0&0\\ 0&0&1&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0 \end{vmatrix} \Rightarrow t_2 \Rightarrow \mu_2(13{,}5)=\begin{vmatrix} 1&0&0&0&0\\ 0&0&0&1&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&1&0&0\\ 0&0&0&1&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0\\ 0&0&0&0&0 \end{vmatrix} \Rightarrow t_1 \Rightarrow$$

As the simulation continues, all network transitions are executed, which means the model is alive and the sequence of launches of triggered transitions takes the form:

$$\delta = \left(t_1, t_2, t_1, t_3, t_4, t_5, t_6, t_7, t_8, t_{10}, t_9, t_{10}\right)$$

The model has been analyzed, the network is alive, periodic and all markings are reachable.

Model of an evolutionary fuzzy controller using CPN in the CPN Tools system. The main point when implementing an evolutionary fuzzy controller (FC) is the coupling of a locally parallel fuzzy control algorithm with an evolutionary procedure. Deliberately incorrect decisions made may appear during testing of the regulator's performance. One of the main requirements for regulators in automatic control is to ensure stability, in connection with ensuring safety[3].

The structure of a locally parallel evolutionary fuzzy controller consists of the following blocks: a control device (CD), a control object (CO), a registration sensor (RS), a converter of an input signal from a clear to a fuzzy form (fuzzifier) (FF), a fuzzy processing block (FE) (fuzzy inference engine), converter of the output signal from a fuzzy to a clear form (DF) (defuzzifier), quality assessment block (QA), registration of results (RR), block of methods for changing parameters (CP), block of best options (BO) (Figure 2). The blocks of an evolutionary fuzzy controller in the role of states are described by the positions of the CPN:

$$P = \left(p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}\right)$$

Where p_1 – unit CD , p_2 – unit CO , p_3 – unit RS, p_4 – unit FF, p_5 – unit FE, p_6 – unit DF, p_7 – unit QA, p_8 – unit RR, p_9 – unit CP, p_{10} – unit BO.

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[3] Бураков, М.Б. Коновалов, А.С., Яковец, О.Б. Эволюционный синтез нечетких регуляторов. // – Санкт-Петербург: Информационно управляющие системы, – 2015. №6, – с. 28-33.

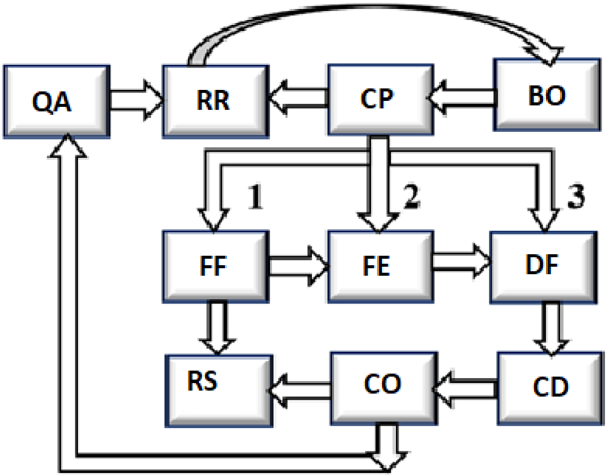

Figure 2. Block schemes of an evolutionary fuzzy controller

Events between states are indicated by transitions [4]:

$$T=(t_1,t_2,t_3,t_4,t_5,t_6,t_7,t_8,t_9,t_{10},t_{11},t_{12},t_{13},t_{14})$$

Where t_1 – is the regulation of input parameters, t_2 – is the registration of input parameters, t_3 – is the conversion of the input signal from a clear form to a fuzzy one, t_4 – is fuzzy processing, t_5 – is the transformation of the output signal from a fuzzy form to a clear form, t_6 – is the formation of an appropriate control action for the input parameter, t_7 – change in the profile of the input terms, t_8 – change in the profile of the output terms, t_9 – change of the decision rules, t_{10} – independent observation of the operation of the system, t_{11} – determination of the target characteristics of the system's functioning, t_{12} – accumulation of experience for each CP option, t_{13} – selection of the best options for parameter changes, t_{14} – installation of the best parameter changes. Input and output incidence

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[4] Гусейнзаде, Ш.С. Анализ свойства устойчивости эволюционного нечеткого регулятора с применением сетей Петри // – Москва: Вестник компьютерных и информационных технологий, – 2019. – №8, – с. 15-22.

matrices F(10,14) and H(14,10) were constructed, on the basis of which a graph model of an evolutionary fuzzy controller was developed in the CPN Tools system (Figure 3).

The initial marking μ_0 is represented by a vector:

$$\mu_0(10)=\left(1,1,0,0,0,0,0,0,1,0\right)$$

During graph simulation, each time transitions are fired, the graph labeling vectors change

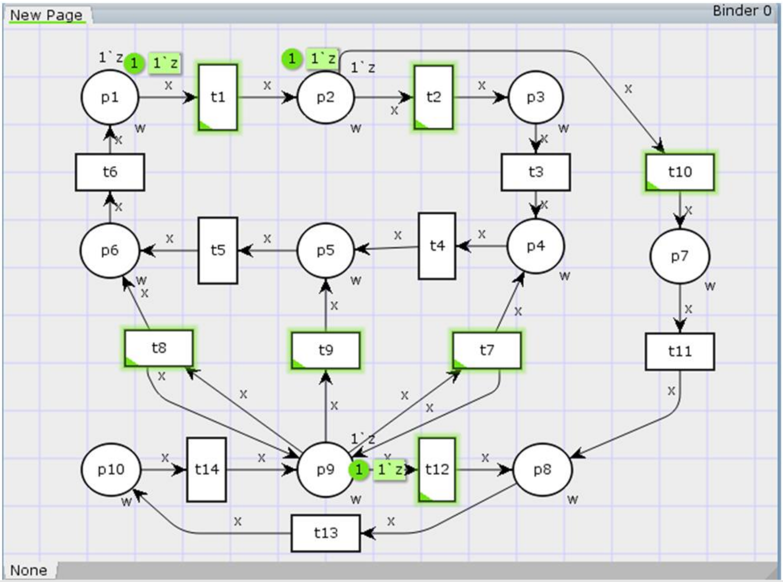

Figure 3. Evolutionary fuzzy controller model on CPN Tools

The sequence of launches of triggered transitions and the marking changes reflected in the vectors are described in the table (Table 1).

Table 1. Triggered transitions and marking changes

Transition	Changes in markings	Transition	Changes in markings
	μ_0=(1 1 0 0 0 0 0 0 1 0);	t_{12}	μ_{23}=(0 0 0 1 0 0 0 2 0 1);

t_1	μ_1=(0 2 0 0 0 0 0 0 1 0);	t_{14}	μ_{24}=(0 0 0 1 0 0 0 2 1 0);
t_2	μ_2=(0 1 1 0 0 0 0 0 1 0);	t_4	μ_{25}=(0 0 0 0 1 0 0 2 1 0);
t_3	μ_3=(0 1 0 1 0 0 0 0 1 0);	t_5	μ_{26}=(0 0 0 0 0 1 0 2 1 0);
t_{10}	μ_4=(0 0 0 1 0 0 1 0 1 0);	t_6	μ_{27}=(1 0 0 0 0 0 0 2 1 0);
t_{11}	μ_5=(0 0 0 1 0 0 0 1 1 0);	t_9	μ_{28}=(1 0 0 0 1 0 0 2 1 0);
t_{13}	μ_6=(0 0 0 1 0 0 0 0 1 1);	t_5	μ_{29}=(1 0 0 0 0 1 0 2 1 0);
t_{12}	μ_7=(0 0 0 1 0 0 0 1 0 1);	t_6	μ_{30}=(2 0 0 0 0 0 0 2 1 0);
t_{14}	μ_8=(0 0 0 1 0 0 0 1 1 0);	t_1	μ_{31}=(1 1 0 0 0 0 0 2 1 0);
t_4	μ_9=(0 0 0 0 1 0 0 1 1 0);	t_1	μ_{32}=(0 2 0 0 0 0 0 2 1 0);
t_5	μ_{10}=(0 0 0 0 0 1 0 1 1 0);	t_2	μ_{33}=(0 1 1 0 0 0 0 2 1 0);
t_6	μ_{11}=(1 0 0 0 0 0 0 1 1 0);	t_3	μ_{34}=(0 1 0 1 0 0 0 2 1 0);
t_7	μ_{12}=(1 0 0 1 0 0 0 1 1 0);	t_{10}	μ_{35}=(0 0 0 1 0 0 1 2 1 0);
t_4	μ_{13}=(1 0 0 0 1 0 0 1 1 0);	t_{11}	μ_{36}=(0 0 0 1 0 0 0 3 1 0);
t_5	μ_{14}=(1 0 0 0 0 1 0 1 1 0);	t_{13}	μ_{37}=(0 0 0 1 0 0 0 2 1 1);
t_6	μ_{15}=(2 0 0 0 0 0 0 1 1 0);	t_{12}	μ_{38}=(0 0 0 1 0 0 0 3 0 1);
t_1	μ_{16}=(1 1 0 0 0 0 0 1 1 0);	t_{14}	μ_{39}=(0 0 0 1 0 0 0 3 1 0);
t_1	μ_{17}=(0 2 0 0 0 0 0 1 1 0);	t_4	μ_{40}=(0 0 0 0 1 0 0 3 1 0);
t_2	μ_{18}=(0 1 1 0 0 0 0 1 1 0);	t_5	μ_{41}=(0 0 0 0 0 1 0 3 1 0);
t_3	μ_{19}=(0 1 0 1 0 0 0 1 1 0);	t_6	μ_{42}=(1 0 0 0 0 0 0 3 1 0);
t_{10}	μ_{20}=(0 0 0 1 0 0 1 1 1 0);	t_8	μ_{43}=(1 0 0 0 0 1 0 3 1 0);
t_{11}	μ_{21}=(0 0 0 1 0 0 0 2 1 0);	t_6	μ_{44}=(2 0 0 0 0 0 0 3 1 0);
t_{13}	μ_{22}=(0 0 0 1 0 0 0 1 1 1);	t_1	μ_{45}=(1 1 0 0 0 0 0 3 1 0).

The model is studied based on the results obtained during network simulation. The sequence of launches of triggered transitions has the form: t_1, t_2, t_3, t_{10}, t_{11}, t_{13}, t_{12}, t_{14}, t_4, t_5, t_6, t_7, t_4, t_5, t_6, t_1, t_1, t_2, t_3, t_{10}, t_{11}, t_{13}, t_{12}, t_{14}, t_4, t_5, t_6, t_9, t_5, t_6, t_6, t_1, t_2, t_3, t_{10}, t_{11}, t_{13}, t_{12}, t_{14}, t_4, t_5, t_6, t_8, t_6, t_1. Based on the map of executed transitions, it is clear that this CPN does not have dead ends, since all transitions have been launched. The reachability problem for this CPN is also solved, all transitions are completed in 45 steps, and the PN is brought to the initial state, which shows the stability of the system “as a whole.” The exception is the marking at position p_8, where the recorded results of the best options using parameter modification methods are accumulated.

The third chapter is devoted to the development of combined and integrated modifications designed to model fuzzy control based on FPN. It is determined that existing FPNs still face difficulties in simulating the inconsistent cognition of experts and the individual characteristics of different systems.

Mathematical formalization of integrated FCPN. An integrated modification of the FCPN is proposed, obtained by integrating the FPN and CPN. The disadvantages and advantages of NSP and RSP in modeling intelligent control models are identified and justified separately. In the developed FCPN, the membership functions of terms of a linguistic variable are applied to CPN markers in the role of color, fuzzy conditions of existence are assigned to arcs, and fuzzy triggering conditions are assigned to transitions. The selection of the membership function and fuzzification of term values is performed in the Fuzzy Toolbox application of the Matlab system. The structure is organized in the CPN TOOLS system with synchronization of the CPN ML language with the MATLAB package. A model has been developed for automating adaptive fuzzy control of the process of turning on and off water pumps according to the water levels in the pump well based on integrated FCPN.

FCPN is represented as a set of non-empty finite sets and functions[5]:

$$FCPN = (P, T, F, H, L, \Upsilon, \Omega, \Sigma, \lambda, \varphi, \psi, \tilde{R}, \tilde{\Delta}, \tilde{G}, \mu^0)$$

Where:

- P и T – espectively, finite sets of positions and transitions:

$$P = \{p_1, p_2, p_3, \ldots\}, T = \{t_1, t_2, t_3, \ldots\};$$

- F и H – respectively, the incident function of the sets of positions and transitions:

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[5] Гусейнзаде, Ш.С., Моделирование интеллектуальных систем управления с применением модифицированных нечетких раскрашенных сетей Петри // – Москва: Вестник компьютерных и информационных технологий. – 2020. – №10, – с. 30-37.

$$F: P \times T \rightarrow \{0,1,2,\ldots\}$$

$$H: T \times P \rightarrow \{0,1,2,\ldots\}$$

- L – a finite set of linguistic variables:x:

$$L = \{\beta_1, \beta_2, \beta_3, \ldots\}$$

- Υ – many colors of positions and colors of markers:

$$\Upsilon = \{\gamma_1, \gamma_2, \gamma_3, \ldots\}$$

- Ω – set of colors of positions and colors of markers:

$$\Omega = \{\omega_1, \omega_2, \omega_3, \ldots\}$$

- Σ – a finite set of variables assigned to arcs:

$$\Sigma = \{\delta_1, \delta_2, \delta_3, \ldots\}$$

- λ – function of distribution of colors of markers by position:

$$\lambda: P \times \Upsilon \rightarrow \{0,1\}$$

- φ – function of distribution of colors of markers by position:

$$\varphi: P \times \Omega \rightarrow \{0,1,2,\ldots\}$$

- ψ – function of resolving the movement of marker colors along arcs:

$$\psi: P \times \Sigma \rightarrow \{0,1,2,\ldots\}$$

- $\tilde{R}$ – a finite set of fuzzy predicates related to transitions, defining additional conditions for the execution of transitions:

$$\tilde{R} = \{\tilde{r}_1, \tilde{r}_2, \tilde{r}_3, \ldots\}$$

- $\tilde{\Delta}$ – a finite set of fuzzy conditions related to arcs that determine the existence of the arc:

$$\tilde{\Delta} = \{\tilde{\sigma}_1, \tilde{\sigma}_2, \tilde{\sigma}_3, \ldots\}$$

- $\tilde{G}$ – set of fuzzy marker color functions that define fuzzy values of terms of linguistic variables:

$$\tilde{G}=\{\tilde{g}_1,\tilde{g}_2,\tilde{g}_3,\dots\}$$

- $\tilde{\mu}_0$ – initial distribution of markers by position:

$$\tilde{\mu}_0 : P\times(\Omega\cup\tilde{G})\to\{0,1,2,\dots\}$$

In the presented modified FCPN, a linguistic variable corresponds to one position, and each term has a certain marker color, which reduces the number of positions to the number of linguistic variables m, which leads to compression of the model space, and an increase in the number of marker colors does not affect the size of the structural elements.

Automation model of adaptive fuzzy control based on integrated FCPN. As an example, a control model for three water pumps on a wastewater well is considered.

The linguistic variable “water level” is defined in the universe U = [0.12] (conventional unit) and has a term set T = {“highly reduced”, “reduced”, “slightly decreased”, “normal”, “slightly increased”, “increased”, “strongly increased”}. For the linguistic variable “water level” in the universe U, seven fuzzy sets were constructed (Figure4):

$$\tilde{A}_1=(0,\ 1.8),\ \tilde{A}_2=(0.2,\ 3.8),\tilde{A}_3=(2.2,\ 5.8)$$

$$\tilde{A}_4=(4.2,\ 7.8),\ \tilde{A}_5=(6.2,\ 9.8)$$

$$\tilde{A}_6=(8.2,\ 11.8),\ \tilde{A}_7=(10.2,\ 12)$$

According to the values of the terms of the set, the constructed membership functions are given names: “hd”, “d”, “sd”, “nor”, “si”, “i”, “hi” (“hd” - highly decreased), “d” - decreased, “sd” - slightly decreased, “nor” - normal, “si” - slightly increased, “i” - increased, “ hi” - highly increased). – *“hd”, “d”, “sd”, “nor”, “si”, “i”, “hi” (“hd”* – highly decreased, *“d”* - decreased (decreased), *“sd” - slightly* decreased (slightly decreased), *“nor”* - normal (normal), *“si”* - slightly increased (slightly increased), *“i”* - increased (increased), *“hi”* - highly increased (highly increased)). сильно понижен (highly decreased).

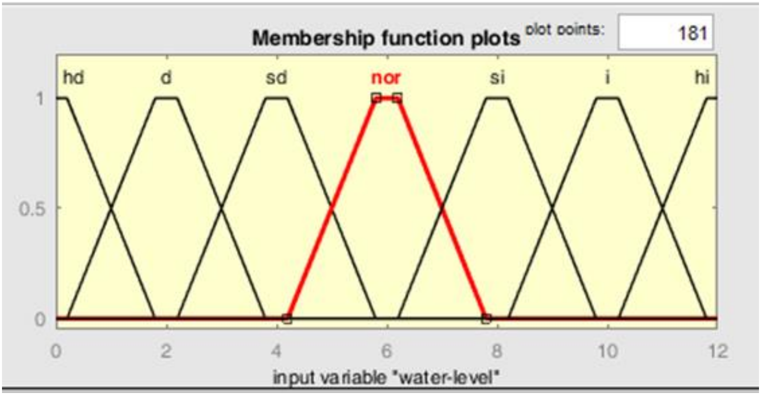

Figure 4. Graphical representation of membership functions for the linguistic variable "water level".

Based on the operating criteria of three water pumps, according to the water levels in the pump well, depending on various states and events in the system, the structural elements are determined:

- **Sets positions**:

$$P = \{WLC, OF1, OF2, OF3, ON1, ON2, ON3\}$$

Where, WLC (water level condition) – receiving information about the state of the water level; OF1 – the first pump is turned off; OF2 – the second pump is turned off; OF3 – the third pump is turned off; ON1 – the first pump is turned on; ON2 – the second pump is turned on; ON3 – the third pump is turned on.

- **Sets of transitions:**

$$T = \{TON1, TON2, TON3, TOF1, TOF2, TOF3\}$$

Where, TON1 is the activation of the first pump; TON2 – switching on the second pump; TON3 – activation of the third pump; TOF1 – shutdown of the first pump; TOF2 – shutdown of the second pump; TOF3 – shutdown of the third pump.

- **Arc set**: All connections between positions and transitions of the model are included in the arc set[6].
- **Arc set:** All connections between positions and transitions of the model are included in the arc set.

The operating algorithm of the CO is described by products, on the basis of which matrices of input and output incidences are formed $F(7,6)$ и $H(6,7)$:

$$F(7,6)=\begin{vmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} \quad H(6,7)=\begin{vmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{vmatrix}$$

The model was developed in a software-tool system using CPN Tools (Figure 5). The standard declaration using CPN ML defines: position colors (WL, POF, PON), marker colors (pof, pon, si, i, hi, nor, sd, d, hd) and variables assigned to arcs (w, f, p).

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[6] Huseynzade, Sh.S. Automation Model of the Adaptive Control on Petri nets // – Kyiv: Bulletin of the Taras Shevchenko National University of Kyiv, a series of physical and mathematical sciences, – 2018. №1, – p. 55-59.

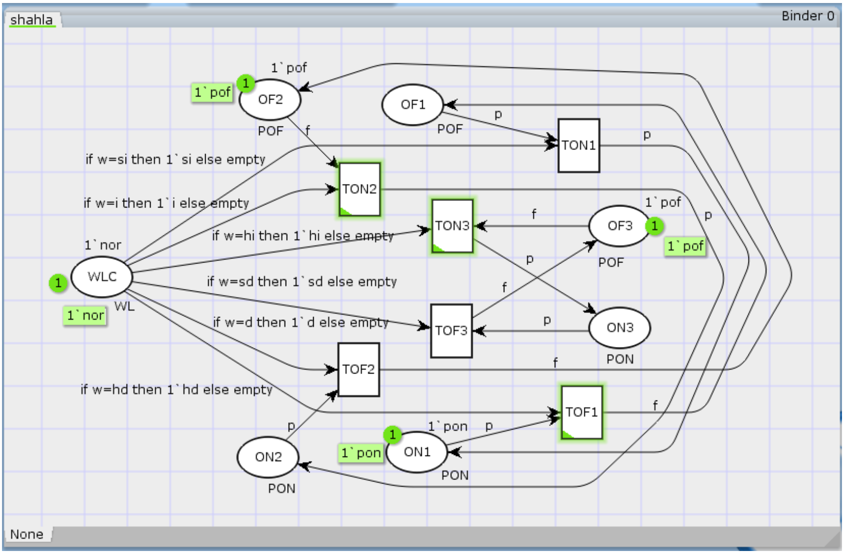

Figure 5. NRSP model in the CPN Tools system

The initial marking corresponding to the state of the system on the presented graph of the model (Figure 5), taking into account the sequence of WLC, OF1, OF2, OF3, ON1, ON2, ON3 positions, will have the form:

$$\mu^0 = \{nor, \varepsilon, pof, pof, pon, \varepsilon, \varepsilon\}$$

Which corresponds to the situation: the state regarding the water level is normal, the first pump is turned on, the second and third pumps are turned off.

The existence conditions are assigned to the arcs in the form of a code expression in the CPN ML language:

If w=si then 1`si else empty; - (if there is a marker “si” in the input position, the corresponding situation is slightly increased) then one marker “si” is transmitted along the arc, otherwise there is no arc):

If w=i then 1`i else empty;
If w=hi then 1`hi else empty;
If w=sd then 1`sd else empty;
If w=d then 1`d else empty;

If w=hd then 1`hd else empty;.

Colors for network markers: markers *“hd”, “d”, “sd”, “nor”, “si”, “i”, “hi”* express the meanings of terms; Markers *“pof”, “pon”* mean the pumps are turned off and on.

Colors for network arcs: *w* resolution of movement of color markers *“hd”, “d”, “sd”, “nor”, “si”, “i”, “hi”* along the arc; *f* – permission to move “pof” color markers along an arc; *p* – permission to move “pon” color markers along an arc.

Colors for network positions: *WL, POF, PON. WL* – permission for the existence of color markers *“hd”, “d”, “sd”, “nor”, “si”, “i”, “hi”* in position; POF and PON allowing the existence of color markers *“pof” and “pon”* in a position.

Using the above initial data, computer experiments were carried out to simulate the network. Based on incoming information, a decision is automatically made to normalize the situation. Markings are formed according to the situations:

$$\mu^1 = \{i, \varepsilon, pof, pof, pon, \varepsilon, \varepsilon\}$$

$$\mu^2 = \{nor, \varepsilon, \varepsilon, pof, pon, pon, \varepsilon\} \text{ и т.д.}$$

The obtained experimental results for various incoming information make it possible to analyze the model by the properties of the FCPN. The simulation demonstrates how quickly the system adapts to the situation.

Modeling using combined FPNs. A combined modification of extended FPN types is presented, where transitions are assigned membership functions of fuzzy triggering and a fuzzy threshold for triggering transitions, and where positions are assigned membership functions of the presence of one marker in the corresponding position. An algorithm for the functioning of the presented modification has been developed, which allows modeling using fuzzy production rules describing the CO. The main parts of production rules are presented in the form of structural elements of a combined modified FPN. A fuzzy model of a production module has been developed in the form of an FPN based on a fuzzy production system. A computer implementation of the model was carried out and a network analysis was performed.

The presented modification of the FPN looks like:

$$N_{cf} = (P, T, I, O, f, \lambda, \mu^0)$$

Where $\tilde{P}$ и $\tilde{T}$ – fuzzy sets of positions and transitions; $I: \tilde{P} \times \tilde{T} \to \{0,1,\dots\}$ and $O: \tilde{P} \times \tilde{T} \to \{0,1,\dots\}$ – functions of input and output incidents, respectively; $f = (f_1, f_2, \dots, f_m)$, $f_j \in [0,1]$, $m \in N$, $j = \overline{1,m}$ (m – number of transitions) – vector of values of the membership function of fuzzy transition activation; $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_m)$, $\lambda_j \in [0,1]$, $m \in N$, $j = \overline{1,m}$ – vector of transition threshold values; $\mu_i^0 \in [0,1]$, $i = \overline{1,n}$. $\mu^0 = (\mu_1^0, \mu_2^0, \dots \mu_n^0)$ (n – number of positions) – vector of initial marking, each component of which is determined by the value of the membership function of the presence of one marker in the corresponding position of this network.

Algorithm for the functioning of the combined modification FPN:

Step 1. Creating an Input Incident Matrix g=$\{g_{ij}\}$, where $i = \overline{1,n}, j = \overline{1,m}$.

Step 2. Creating an output incident matrix $h=\{h_{ji}\}$, где $i = \overline{1,n}, j = \overline{1,m}$..

Step 3. Creation of an initial marking vector, where $\mu = \{\mu_i\}$, где $i = \overline{1,n}$ each component μ_i is determined by the value of the membership function of the fuzzy presence of one marker in the corresponding position of a given network.

Step 4. Creation vector $\lambda = \{\lambda_j\}$, where $j = \overline{1,m}$ and each component is determined by the threshold value of the transition firing t_j.

Step 5. Creation vector $f = \{f_j\}$, where $j = \overline{1,m}$ and each component f_j is determined by the value of the fuzzy transition firing membership function t_j.

Step 6. Creation vector $c=\{c_i\}$, где $i=\overline{1,n}$ and components c_i are used to fix the numbers of input and output positions of an enabled transition.

Step 7. Переход Search for an allowed transition. Transition t_j is allowed if the condition is satisfied for the minimum value of the membership function of the fuzzy presence of one input position marker – $min\{\mu_i\} \geq \lambda_j$:

a) counter k is determined (initial value k=0), to count the number of input positions t_j;

b) for each $g_{ij} \neq 0$ for $i=\overline{1,n}$ the counter is added by one and the position number is fixed: $k=k+1,\ c_k=i$;

c) $\mu_{min}=\mu_i$, where $i=c_1$ (μ_{min} – identifier for assigning the minimum value of the input position membership function t_j);

d) if $\mu_i<\mu_{min}$ то $\mu_{min}=\mu_i$. for $i=c_l$, $l=\overline{2,k}$;

e) if $\mu_{min} \geq \lambda_j$ then transition t_j is enabled, transition to step 9 is carried out.

Step 8. If for transition t_j the triggering condition is not met, then index j is increased by one: $j=j+1$. When $j \leq m$, the transition is made to item a) of step 7, otherwise a message about the deadlock state and the end of the search is displayed, and the transition is made to step 11.

Step 9. Formation of the next marking vector $\mu'=(\mu'_1,\mu'_2,\dots,\mu'_n)$: after the transition is triggered t_j.

9.1. For all fixed input transition positions t_j, the values of the membership functions of the fuzzy presence of one marker are equal to zero: $\mu'_i=0$, где $i=c_l$, $l=\overline{1,k}$.

9.2. Calculation of membership function values for the fuzzy presence of one output position marker:

a) counter k is determined (initial value $k=0$), to count the number of output positions t_j:

b) for each $h_{ji} \neq 0$ for $i=\overline{1,n}$, the counter is added by one and the position number is fixed: $k=k+1,\ c_k=i$;

c) $\mu_{max}=\mu_i$, where $i=c_1$ (μ_{max} – dentifier for assigning the maximum value of the output position membership function t_j);

d) if $\mu_i > \mu_{max}$ then $\mu_{max} = \mu_i$. for $i=c_l$, $l=\overline{2,k}$;

e) if $\mu_{min} >$ f_j then $\mu_{min} =$ f_j ;

f) if $\mu_{max} < \mu_{min}$ то $\mu_{max} = \mu_{min}$;

g) for all fixed output positions of the transition t_j, the values of the membership functions of the fuzzy presence of one marker are calculated according to the rule: $\mu_i' = \mu_{max}$, where $i=c_l$, $l=\overline{1,k}$.

Step 10. The process can be completed (go to step 11) or continue (go to step 7).

Step 11. *End.*

Model of a production module control system using combined FPN. Using the example of a module for opening a cylindrical hole in the channel formation section of aluminum evaporators, fuzzy production rules were formed. The formation of a channel for aluminum evaporators is carried out using the following technology: the semi-finished aluminum evaporator from the previous position is moved by an automatic transport system 1 to the position of the lifting and positioning manipulator 1 of an industrial robot; after positioning the semi-finished product, the industrial robot moves it to the position of the lifting-positioning manipulator 2 of the device for opening the cylindrical hole; the device for opening the cylindrical hole is turned on and the operation of opening the cylindrical hole is performed using a special device; at the end of the operation, the industrial robot grabs the semi-finished product and moves it to the position of the automatic transport system 2, which delivers the workpiece to the position of the hydraulic press equipped with special stamps, where the channel formation operation is performed. Next, the process is repeated in a cyclic mode as the semi-finished product arrives from the previous position[7].

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[7] Мустафаев, В.А., Гусейнзаде, Ш.С., Джафарова, Ш.М. Анализ продукционных моделей динамических взаимодействующих процессов с применением модифицированных нечетких сетей Петри // – Москва: Вестник компьютерных и информационных технологий, – 2017. №2(146), – с. 21-25.

It is known that the height of the cylindrical hole (HCH) should be within 10±2 mm, and the cross-sectional diameter of the cylindrical hole (DCH) should be 4±0.5 mm. System of fuzzy production rules (where FP – semi-finished product):

Rule 1. If HCH slightly above normal (p_4) ***and*** DCH slightly above normal (p_5), ***then*** FP is normal (p_3).

Rule 2. If HCH slightly normal (p_8) ***and*** DCH slightly normal (p_9), ***then*** FP accepted into the control system (p_{12}).

Rule 3. If HCH much below normal (p_{13}) ***and*** DCH much below normal (p_{14}), ***then*** FP not accepted into the control system (p_{17}).

Rule 4. If HCH normal (p_1) ***and*** DCH normal (p_2), ***then*** FP is normal (p_3).

Rule 5. If HCH slightly below normal (p_6) ***and*** DCH slightly below normal (p_7), ***then*** FP is normal (p_3).

Rule 6. Если HCH below normal (p_{10}) ***and*** DCH below normal (p_{11}), ***then*** FP accepted into the control system (p_{12}).

Rule 7. If HCH much below normal (p_{15}) ***and*** DCH much below normal (p_{16}), ***then*** FP not accepted into the control system (p_{17}).

Rule 8. If FP accepted into the control system (p_{12}), ***then*** FP normal (p_3) ***or*** FP defective (p_{18}).

Rule 9. If FP not accepted into the control system (p_{17}), ***then*** FP defective (p_{18}).

All conditions and conclusions of fuzzy production rules are defined as positions FPN:

$$P=\{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{10}, p_{11}, p_{12}, p_{13}, p_{14}, p_{15}, p_{16}, p_{17}, p_{18}\}$$

Transitions are determined in accordance with the rules of fuzzy productions: $T=\{t_1, t_2, t_3, t_4,\ t_5, t_6, t_7, t_8, t_9\}$

Vectors of fuzzy triggering, threshold and initial transition marking function values are determined from static data:

$$f=(0.8;\ 0.7;\ 0.6;\ 0.5;\ 0.4;\ 0.3;\ 0.2;\ 0.2;\ 0.1)$$

$$\lambda=(0.8;\ 0.7;\ 0.6;\ 0.5;\ 0.4;\ 0.3;\ 0.2;\ 0.2;\ 0.1)$$

$$\mu_0 = \left(0.9;0.9;0;0.8;0.8;0.7;0.7;0.6;0.6;0.5;0.5;0;0.4;0.4;0.3;0.3;0;0\right)$$

With the computer implementation of the developed algorithm, vectors of achievable markings were obtained:

– The first solvable transition is t_1, since, $I(t_1) = \{p_1, p_2\}$, $\mu_1^0 = 0.9 > 0$, $\mu_2^0 = 0.9 > 0$ and the condition $min\{\mu_1^0, \mu_2^0\} \geq \lambda_1$ ($min\{0.9, 0.9\} \geq 0.8$) satisfied. t1. Transition t_1 fires. For input p_1, p_2 and output p_3 позиций positions, the marking components are calculated: $\mu_1^1 = 0$, $\mu_2^1 = 0$,

$$\mu_3^1 = max\left\{\mu_0(p_3), min\ (0.9, f_1)\right\} = max\left\{0; min(0.9; 0.8)\right\} =$$

$$= max\left\{0;0.8\right\} = 0.8$$

The marking $\mu^1 = (\mu_1^1, \mu_2^1, \dots, \mu_{18}^1)$ is:

$$\mu^1 = \left(0;0;0.8;0.8;0.8;0.7;0.7;0.6;0.6;0.5;0.5;0;0.4;0.4;0.3;0.3;0;0\right)$$

Transitions t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9 are triggered sequentially. The behavior of the simulated system is analyzed by the basic properties of the PN.

The combined modification of the FPN provides: a visual representation of the structure of the rules of fuzzy productions and the implementation of fuzzy logical conclusions based on them

Combined extended modification of SPN. A combined SPN was formed, in which stochastic parameters were simultaneously applied to two structural elements at the same time - transitions and markers in positions based on the presented SPN types. The modification is formed as follows:

The combined modification of the SPN is determined by the five $N_S^I = (P, T, W, \Omega, \mu^s)$, where, $P=\{p_1,p_2,\dots,p_n\}$, $n>0$ *is a finite non-empty set of positions;* $T=\{t_1, t_2, \dots, t_m\}$, $m>0$ – finite non-empty set of transitions; $W:(P\times T) \cup (T\times P) \to N$ *N* – function of weights of arcs between places and transitions and vice versa (*N* – set of natural numbers);

I:P×T→$(0,1,\dots)$; $O:T\times P\to(0,1,\dots)$ – functions of input and output interventions, respectively), $\Omega: T\to IR_+$ − transition rate function $IR_{+}=[0;\infty)$ − continuous time scale), and the mapping $\mu^{S}:P \to V_{s}=[0,1]$ assigns a distribution vector to each position probabilities of having chips $\mu^{S}(p_i)$.

Algorithm for the functioning of the combined SPN:

Step 1. Creating a matrix of input and output incidents and transition rates, $F=\{h_{ij}\}$, $H=\{h_{ji}\}$, $\Omega=\{\theta_j\}$, where $i=\overline{1,n},\ j=\overline{1,m}$ . .

Step2. Create initial markings $\mu=\{\mu_i\},i=\overline{1,n},$

Step 3. Determining the matrix $S=\{s_c\}$, where $c=\overline{0,m}$ to fix the numbers of allowed transitions.

Step 4. Finding an allowed transition:

a) all $f_{ij}\neq 0$ are selected, with $i=\overline{1,n}$;

b) for each fixed *i* there must be $\exists \mu_i \neq 0$.

Step 5. If for transition t_j the triggering condition is met, the number of this allowed transition is fixed: $c=c+1;\ s_c=j$ c=c+1;

Step 6. Index *j* is increased by one: $j=j+1$. When $j\leq m$, the transition to point a) of step 4 is carried out, otherwise if c = 0, then a deadlock message is displayed, the search is completed and the transition to point 13 is carried out.

Step 7. Selecting transition t_j with the highest rate θ_j among fixed transitions, with $j=s_i$, where $i=\overline{1,c}$;

Step 8. Calculation of the probability of triggering of the allowed transition t_j in marking μ_i: $PF(t_j)=\theta_j \,/\, \sum_{i=1}^{c}\theta_{s_i}$

Step 10. Formation of the probability distribution vector for each input position after the transition t_j: $\mu_i'=\mu_i-f_{ij}$;

Step 11. Formation of the probability distribution vector for each output position after the transition is triggered: $\mu_i'=\mu_i+h_{ji}$;

Step 12. At the user's choice, either the process continues and proceeds to step 5, or the process stops and proceeds to step 13.

Step 13. End.

The integrated CSPN is a combination of colored and stochastic PNs. To obtain the structure of the CSPN, it is necessary to add to the SPN the components of the CPN: C – marker color function, which in this case determines the colors of each of the markers $M(p_i)$ for network positions; V – conditions for triggering transitions depending on the color of the marker; K is the capacity of markers in positions taking into account C. In the integrated CSPN, color attributes can be assigned to individual structural elements as in the CSPN,and stochastic parameters and logical conditions for triggering transitions can be applied as in the SPN.

A model of the process of occurrence and elimination of malfunctions of a technical system has been developed in the form of an integrated CSPN on CPN Tools. Each transition is assigned a time stamp, the value of which determines the time the marker remains in the corresponding position, where the matrix of transition rates in the developed CSPN model is represented by a vector of model times. The change in markings occurs for two reasons: the fulfillment of the transition triggering condition and the completion of the transition delay time.

Based on known statistical data on failure rates and the duration of troubleshooting operations, replacement and repair of a failed unit, the structural elements of the CSPN were formed.

The number of faulty blocks, the rate of occurrence of failures, the rate of search for faulty blocks and restoration of blocks, etc. can be random. Each transition $t_j \in T$ is associated with a tempo $\theta_j \in \Omega$. Based on the input and output incidence functions, arcs are constructed between the positions and transitions of the RSSP. During computer simulation, a sequence of triggered transitions and vectors of the probability distribution of the presence of tokens were obtained. The model allows you to resolve conflict situations and prevent deadlocks in an integrated CSPN.

The fourth chapter is devoted to the modeling of fuzzy control based on a hybrid approach using FCPN, which combines methods focusing on model abstractions (integrated FCPN) and logical abstractions (fuzzy inference method), and includes two software tools - the Fuzzy Toolbox application of the MATLAB modeling system and simulation platform CPN Tools based on PN.

With the introduced fuzzy inference mechanism, FCPN provides a linguistic approach using the software-tool platform CPN Tools. According to the obtained values, decisions are made, the functioning of the FCPN is carried out and an imitation of the functioning of the controlled system is realized.

Fuzzy control model based on a hybrid approach using NRSP. The most important task when developing an ICS for a pumping system is to model the engine control system for more accurate and smooth adjustment of speed (engine speed) within load limits, according to water consumption modes. Water consumption has uncertainties in nature - pronounced fluctuations over time. According to the unclear nature of changes in water flow over time, pumping equipment should be continuously adjusted.

When developing a fuzzy control model for speed control of a pumping unit, the basic principles of control (not detailed design) are considered when operating according to changing daily water consumption. During the operation of the system, current information is converted into linguistic quantities using the fuzzification procedure. Using the rule base, a logical solution is formed. The system of production rules that describe cause-and-effect relationships between states and events in the system is modified into an algorithm that is implemented both graphically and programmatically, as a result of which a computer study of the system is carried out.

The initial stage of solving the problem consists of the formation of universes of fuzzy parameters. In hydrodynamics, the Navier – Stokes equations are mainly used to describe the flow of liquids at each point in the flow. But the calculation of each individual spatial point of the flow is impossible due to its high labor intensity; the existing analytical technique is insufficient to solve the famous problem. One of the frequently practiced approximate methods for solving this problem is to construct a daily step schedule. Taking into account the stated aspects, a daily stepwise schedule was constructed with a specific calculation of 74 l/sec of water consumption per ten thousand conventional inhabitants in

Azerbaijan and with a characteristic coefficient according to the EN 752 standard in the MATLAB system (Figure 6).

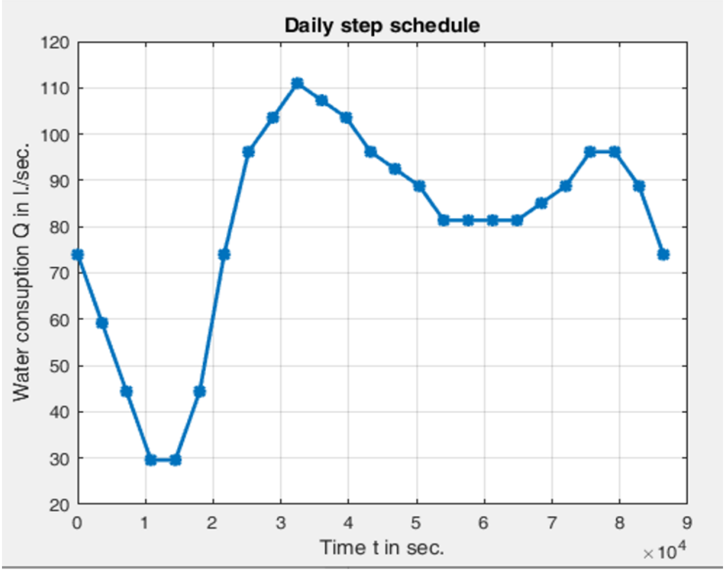

Figure 6. Daily step chart of water consumption

The variable t in the graph (Figure 6) is time with an interval of 3600 seconds. The variable in the graph is the water flow at the corresponding time values and the value of the characteristic curve. The interval (20.120) covers the weight range (with a reserve addition) of changes in water consumption per 10,000 conventional inhabitants; the interval (0.1000) is chosen as the conditional range for changes in pump speed.

Fuzzification of variables. The linguistic variable “water consumption” is defined in the set (universe) $X_{рв} = (20,120)$ l/sec. and has a term set:

$$T_{\text{water consuption}} = \{«small», \ «medium», \ «larce»\}$$

According to the values of the terms of the set $T_{\text{water consumption}}$, three membership functions of piecewise linear triangular type are constructed in graphical form (Figure 7), which are named “nb”, “sr”, “b” according to the names of the terms.

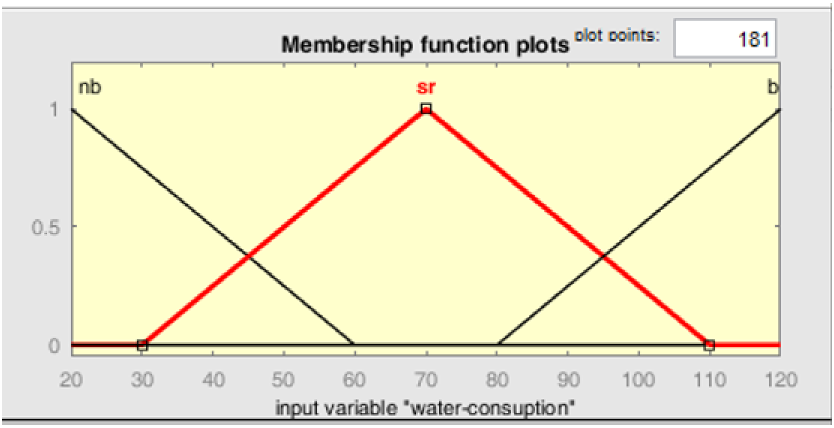

Figure 7. Linguistic membership functions variable "water consumption"

For the linguistic variable “water consumption”, three fuzzy sets are constructed according to its terms:

$$\tilde{A}_1 = (20,\ 60); \tilde{A}_2 = (30,\ 110); \tilde{A}_3 = (80,\ 120)$$

The linguistic variable “pump speed” is defined in the set (universe) $X_{CH} = [0,1000]$ (conventional unit) and has a term set:

$$T_{pumpspeed} = \{«love»,\ «medium»,\ «high»\}$$

According to the values of this term set, the membership functions constructed in graphical form are named “sn”, “ss”, “sv” according to the names of the terms (Figure 8).

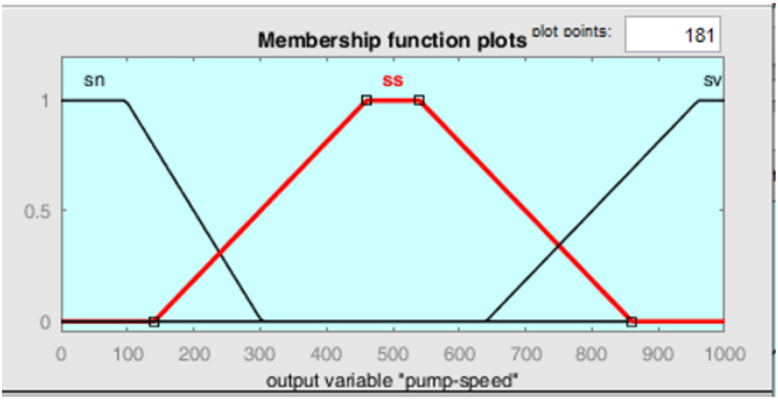

Figure 8. Linguistic membership functions variable "pump speed"

From the figure (Figure 8) it is clear that for the linguistic variable "pump speed" in the universe X_{ps} three fuzzy sets have been constructed according to its terms "low", "medium", "high":

$$\tilde{B}_1 = (0,\ 302.4); \tilde{B}_2 = (140,\ 860); \tilde{B}_3 = (640,\ 1000)$$

In the "Rule Editor" window of the Fuzzy Toolbox application, fuzzy rules are generated to create a rule base with the help of which a fuzzy logical solution is carried out - the Mamdan algorithm[8]:

If ("water consumption" is nb) then ("pump speed" is sn);
If ("water consumption" is sr) then ("pump speed" is ss);
If ("water consumption" is b) then ("pump speed" is sv).

In the window for viewing the execution of rules "Rule Viewer: PUMP CONTROL", a graphical display of fuzzy output is implemented (Figure 9).

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[8] Huseynzade, Sh.S. Regulation of the pumping unit speed according to changing daily water consumption by the method of fuzzy inference // Tallinn: The Baltic Scientific Journals PIRETC–2021, – v. 14, – issue 04, – p. 85-90.

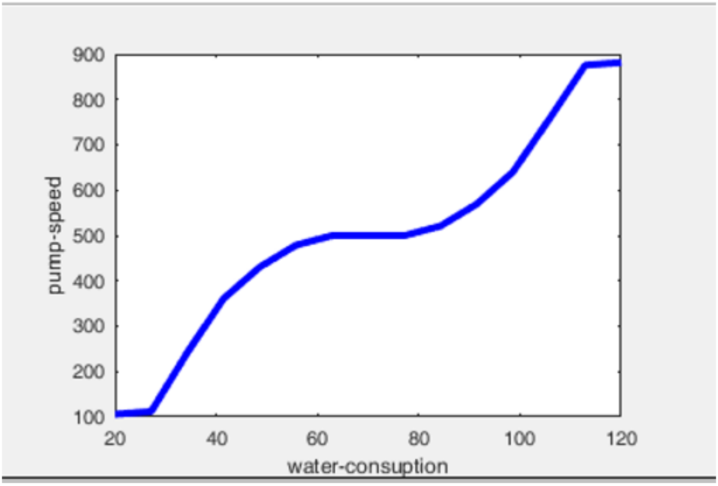

Figure 9. Graphical display of fuzzy output

In the window for viewing the execution of rules "Rule Viewer: PUMP CONTROL" computer experiments are implemented for different values (Figure 10):

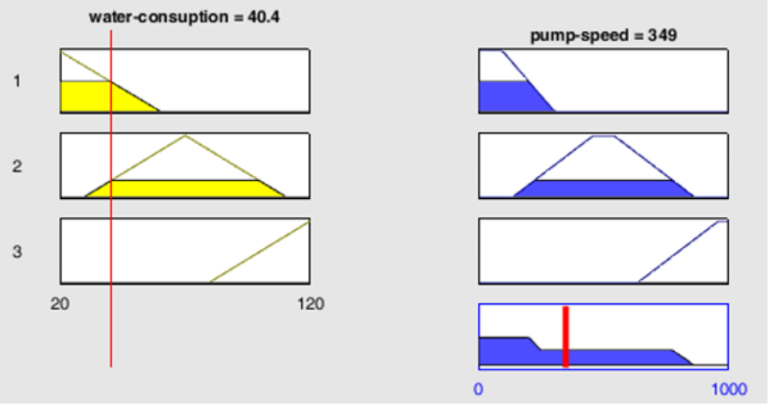

Figure 10. Visualization of the results of rules execution

Numerous experiments were performed by introducing different input values of the variable "water consumption", and the corresponding values of "pump speed" were obtained (Table 2).

Table 2. Results of logical inference

«расход воды»	«скорость насоса»	«расход воды»	«скорость насоса»
21.5	107	84.9	528
27.8	113	92.9	582
34.9	117	99.5	653
40.9	349	102.5	688
56.9	485	107.5	799
70.5	500	118.3	891

Based on various states and events when controlling the operation of water pumps, many positions and transitions of PN were formed:

- Positions: p_1 – the registration sensor has input information; p_2 – pump is on; p_3 – pump is turned off; p_4 – no water flow; p_5 – low water consumption; p_6 – average water consumption; p_7 – high water consumption; p_8 – pump speed is low; p_9 – average pump speed; p_{10} – pump speed is high;
- Transitions: t_1 – input of data from the registration sensor into the system; t_2 – pump activation; t_3 – pump shutdown; t_4 - do not turn on the pump; t_5 – set the operating speed to a low value; t_6 – transfer the operating speed to the average value; t_7 – set the operating speed to a high value.

Production rules of a fuzzy control system for a pumping unit:

1. If there is input information in the registration sensor, then enter data from the registration sensor into the system;
2. If there is no water flow and the pump is turned off, then do not turn on the pump;
3. If there is no water flow and the pump is turned on, then turn off the pump;
4. If the water flow is small and the pump is turned off, then turn on the pump;
5. If the water flow is small and the pump is on and the pump speed is average, then set the operating speed to a low value;

6. If the water flow is small and the pump is on and the pump speed is high, then set the operating speed to a low value;

7. If the water flow is small and the pump is on and the pump speed is low, then do not change the pump speed;

8. If the water flow is average and the pump is turned off, then turn on the pump;

9. If the water flow is average and the pump is on and the pump speed is low, then turn the operating speed to the average value;

10. If the water flow is average and the pump is turned on and the pump speed is high, then change the operating speed to the average value;

11. If the water flow is average and the pump is on and the pump speed is average, then do not change the pump speed;

12. If the water flow is high and the pump is turned off, then turn on the pump;

13. If the water flow is large and the pump is on and the pump speed is low, then change the operating speed to a high value;

14. If the water flow is large and the pump is turned on and the pump speed is medium, then change the operating speed to a high value;

15. If the water flow is large and the pump is on and the pump speed is high, then do not change the pump speed.

Based on the production rules presented above, matrices of input and output incidents were constructed:

$$F\left(10,7\right)=\begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{vmatrix}$$

$$H\left(7,10\right)=\begin{vmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix}$$

Taking into account the values of the elements of the incidence matrices $F(10,7)$ and $H(7,10)$, a management model for the FCPN was built (Figure 11). The structure is organized in the CPN Tools system with synchronization of the CPN ML language with the MATLAB package.

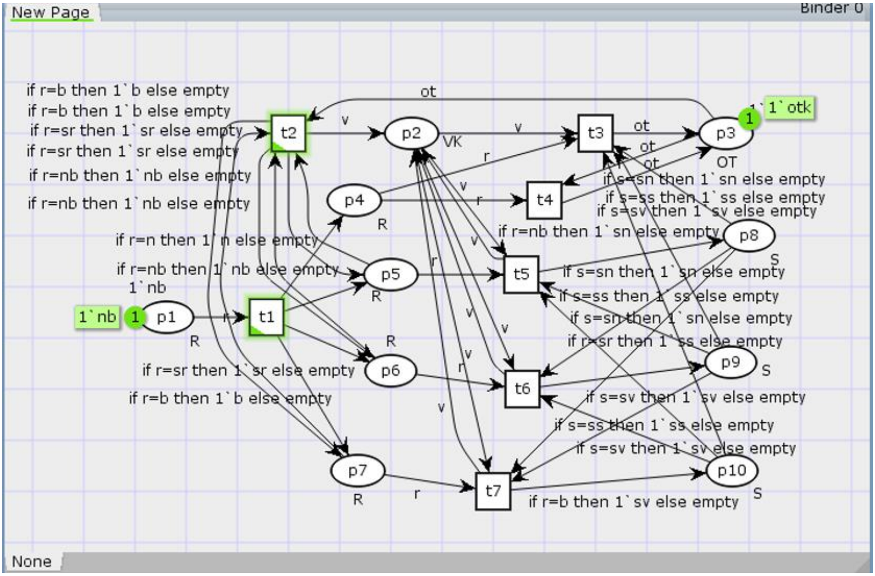

Figure 11. Graph model of the NRSP control of the pumping unit in the initial state of the network simulation

To build a graph model in the CPN Tools system, a standard declaration of variables and attributes of network elements using CPN ML are described:

Standart Declarations
colset R=unit with n|nb|sr|b;   var r:R;
colset S=unit with sn|ss|sv;   var s:S;
colset OT = unit with otk;   var ot:OT;
colset VK = unit with vk;   var v:VK;

Conditions for the existence and permission to move a marker of a given color along them are assigned to the arcs; “empty” means the emptiness of the arc:

If r = nb then 1`nb else empty;

– If there is a “nb” marker at the input position, the flow rate corresponding to the situation is small, then one “nb” marker is transmitted along the arc, otherwise there is no arc.

If r = sr then 1`sr else empty;

If r = b then 1`b else empty;
If r = n then 1`n else empty.

Markers are assigned colors (n), (nb), (sr), (b), (sn), (ss), (sv), (otk), (vk). Identifiers – nb, sr, b correspond to the values of the linguistic variable “water flow”, n – means no water flow, sn, ss, sv correspond to the values of the linguistic variable “pump speed”, otk, vk correspond to the values pump off, pump on.

The initial marking determines the starting situation for the simulation of the graph of the FCPN model and has the form:

$$\mu^0 = \{nb, \varepsilon, otk, \varepsilon, \varepsilon, \varepsilon, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$

where ε means empty marker. μ^0 corresponds to a situation (Figure 13), in which there is input information about a change in water flow and the pump is off, t_1 is triggered, the marking looks like:

$$\mu^1 = \{\varepsilon, \varepsilon, otk, \varepsilon, nb, \varepsilon, \varepsilon, \varepsilon, \varepsilon, \varepsilon\}$$

Computer experiments were carried out to simulate the network with different markings, according to the situations in the system, and the network was analyzed. Based on the resulting NRSP reachability tree, the properties of the model were determined, such as safety, limitedness, liveliness, and reachability. The developed NCPN satisfies the limitation condition, since the maximum number of markers in the model graph does not exceed the number three, which in turn ensures the safety of the model. Simulation experiments demonstrate the viability of the model, since there are no deadlock situations and all transitions are feasible, requiring states are achievable.

The fifth chapter examines some aspects in the development of intelligent models for studying the behavior of complex DS associated with the use of FA.

Despite the fact that a powerful tool for studying the behavior of technical and economic objects is the PN simulation modeling apparatus, for many objects and processes at a low level, the modules of individual system processes are traditionally described by FA. On the other hand, when managing complex DS, it is necessary to take into account not only the processes themselves, but also their interaction, which is why, at a high level, the task of converting FA into PN is important for analysis and formal verification.

The problem of transforming a FA into a PN is considered on the basis of matrix theory; a methodology for constructing structural elements and incidence matrices of a PN is presented, which models a finite automaton described by tables of transitions and outputs. An algorithm has been developed to automate the transformation of tables of transitions and outputs of the FA into a matrix of input and output incidents of the PN[9].

A demonstration of the functioning of the algorithm is given based on a simple model of the functioning of the transport system (TS) of a flexible automated section (FPS). Based on the incidence matrix obtained as a result of the operation of the algorithm, a PN model was built in the form of a graph simulating a spacecraft. The software implementation of the algorithm is carried out in a cross-platform object-oriented programming system C++.

The spacecraft is specified by the functions of transitions and outputs:

$$\varphi:(X \times U) \rightarrow X$$

$$\psi:(X \times U) \rightarrow Y$$

Where: $X = (x_1,\ x_2, \dots ,\ x_z)$ is a finite set of internal states of the machine, $U = (u_1,\ u_2, \dots ,\ u_m)$ is a set of input signals, $Y = (y_1,\ y_2, \dots ,\ y_g)$ is a set of output signals signals, $z \in N$, $m \in N$, $g \in N$ are finite numbers.

φ: (x, u) – transition function of the automaton, defining a unique mapping of the set of pairs (x, u), where $u \in U$ and $x \in X$, into the set X;

ψ: (x, u) – function of the automaton’s outputs, defining a unique mapping of the set of pairs (x, u), where $u \in U$ and $x \in X$, into the set Y;

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[9] Ахмедов, М.А., Гусейнзаде, Ш.С., Насирова, Е.А. Разработка алгоритма автоматизации преобразования конечного автомата в сеть Петри // – Москва: Автоматизация. Современные технологии. – 2019. Т. 73, №3, – с. 108-112.

$x_0 \in X$ – initial state of the machine;

The FA can be specified in the form of a graph, tables of transitions and outputs, and analytical methods.

The functions of transitions and outputs $\varphi: (x, u)$ and $\psi: (x, u)$ FA are presented in a tabular manner (Table 3), (Table 4):

Table 3. FA transition table

	x_1	x_2	…	x_z
u_1	$\varphi(x_1, u_1)$	$\varphi(x_2, u_1)$	…	$\varphi(x_z, u_1)$
u_2	$\varphi(x_1, u_2)$	$\varphi(x_2, u_2)$	…	$\varphi(x_z, u_2)$
⋮	⋮	⋮	⋮	⋮
u_m	$\varphi(x_1, u_m)$	$\varphi(x_2, u_m)$	…	$\varphi(x_z, u_m)$

$$\varphi:\left(x_i, u_j\right) \rightarrow \begin{cases} x_k, & if \quad x_i \wedge u_j \in {}^{\bullet}x_k; \\ \varepsilon, & else. \end{cases}$$

Where $(k = \overline{1, z})$, $\varepsilon - empty\ elments.$

Table 4. Table of FA outputs

	x_1	x_2	…	x_z
u_1	$\psi(x_1, u_1)$	$\psi(x_2, u_1)$	…	$\psi(x_z, u_1)$
u_2	$\psi(x_1, u_2)$	$\psi(x_2, u_2)$	…	$\psi(x_z, u_2)$
⋮	⋮	⋮	⋮	⋮
u_m	$\psi(x_1, u_m)$	$\psi(x_2, u_m)$	…	$\psi(x_z, u_m)$

$$\psi:\left(x_i, u_j\right) \rightarrow \begin{cases} y_k, & if \quad x_i \wedge u_j \in {}^{\bullet}y_k; \\ \varepsilon, & else. \end{cases}$$

Where $k = \overline{1, g}$, ε – $empty\ elments.$

A matrix of transition indices $C = \{c_{j,i}\}$ is formed based on the

FA transition table[10] (table 3.):

$$c_{j,i}=\begin{cases}k, & if \quad \varphi:(x_i,u_j)\to x_k;\\ 0, & if \quad \varphi:(x_i,u_j)\to \varepsilon.\end{cases}$$

where $i=\overline{1,z}$; $k=\overline{1,z}$; $j=\overline{1,m}$.

A matrix of output indices $B=\{b_{j,i}\}$ is formed based on the output table FA (table 4.):

$$b_{j,i}=\begin{cases}k, & if \quad \psi:(x_i,u_j)\to y_k;\\ 0, & if \quad \psi:(x_i,u_j)\to \varepsilon.\end{cases}$$

where $i=\overline{1,z}$; $k=\overline{1,g}$; $j=\overline{1,m}$.

It is known that the PN input incident matrix $F=\{f_{i,j}\}$is defined as

$$f_{ij}=\begin{cases}1, & if \quad p_i\in {}^{\bullet}t_j \ ;\\ 0, & else.\end{cases}$$

The PN output incident matrix $H=\{h_{j,i}\}$ is defined as

$$h_{ji}=\begin{cases}1, & if \quad p_i\in t_j^{\bullet} \ ;\\ 0, & else.\end{cases}$$

where $i=\overline{1,n}$; $j=\overline{1,m}$; (n– namber of pozision, m–namber of tranzision).

The presented technique for solving the problem of transforming a FA into a PN based on matrix theory is reduced to the formation of the values of the elements of the input and output incidence matrices of the PN based on the values of the elements of the transition and output indices matrices of the FA. Based on the existing topology of transforming the FA into a PN and the research

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[10] Huseynzade, Sh.S. Transformation of finite automata tables into incident matrices of Petri net // Proceedings of the 7th International Conference COIA–2020, – Baku: BSU, – 26 – 28 August, – 2020, v.2, – p. 173-176.

carried out regarding the solution of the problem, a method is presented based on the put forward and proven theorems:

Theorem 1. Each non-zero element of the FA transition indices matrix corresponds to unit elements of the matrices of input and output citations of the PN simulating a given FA, which are determined by the following formulas:

$f_{m+i,j} = 1$, $f_{j,j} = 1$ and $h_{j,m+k} = 1$; where $i = \overline{1,z}$; $k = \overline{1,\mathrm{z}}$; $j = \overline{1,m}$. (m – number of input signals, z – number of internal states)

Theorem 2. Each non-zero element of the matrix of output indices of the FA corresponds to unit elements of the matrices of input and output citations of the PN simulating a given FA, which are determined by the following formulas:

$f_{m+i,j} = 1$, $f_{j,j} = 1$ and $h_{j,m+z+k} = 1$; где $i = \overline{1,z}$; $k = \overline{1,\mathrm{g}}$; $j = \overline{1,m}$. (m, g – respectively, the number of input and output signals, z is the number of internal states).

An algorithm has been developed to automate the transformation of tables of transitions and outputs of a FA into a matrix of input and output incidents of a PN; the software implementation of the algorithm is carried out in a cross-platform object-oriented programming system C++. Based on the given models in the form of a FA, the implementation of the algorithm was demonstrated and verification was carried out, computer experiments were carried out, and reliable results were obtained.

The presented approach for converting a FA into a PN has a significant role in modeling complex discrete systems, including those operating in an uncertain environment. With this conclusion, the question arises about the significance of the presented method for converting FA into PN when modeling complex discrete systems, since classical FA cannot deal with system uncertainty. The question is determined by the fact that the method ensures the structural transformation of the FA into the PN and at the same time the personal properties of all structural elements are preserved. FA and fuzzy or stochastic FA do not differ in static structure; there is a difference between them in the qualitative parameters of structural elements and functions of transitions and outputs of the machine. In this case, the structural transformation of distinctive types, in the particular case of ordinary and fuzzy, stochastic FAs into PNs, are combined into one task. In accordance with the properties of the structural elements, the PN takes upon transformation a certain extended structure, including a fuzzy one.

CONCLUSION

1. An analysis of research in the field of ICS of complex DS was carried out based on literature sources, and it was concluded that the constructed models are not very close to the real behavior of complex DS and the increase in the efficiency of DS modeling is determined by the use of modern AI trends. To interpret the features of various complex DS, an approach based on simulation modeling with various extended modifications of the PN and their combining types is justified. For use as a basic software tool, the choice of the CPN Tools system with the open principle of introducing software modules to individual structural elements of the model and the ability to conduct simulation experiments is justified.

1. Разработаны математическое представление и алгоритм функционирования обобщенных РСП, который объединяет две концепции – перерождающие и селективные РСП, где к условиям выполнения переходов введены дополнительные правила определения цветов входящих и исходящих маркеров.

2. A mathematical representation and algorithm for the functioning of generalized CPNs have been developed, which combines two concepts - degenerative and selective CPNs, where additional rules for determining the colors of incoming and outgoing markers have been introduced to the conditions for performing transitions. The expansion of the modeling capabilities of generalized CPNs is justified, especially when modeling and verifying the means of controlling FPS processes. The algorithm is implemented using the CPN ML language, on the basis of which a control model for the FPS processing center module was developed.

3. A model has been developed to determine the stability “as a whole” of an evolutionary fuzzy controller in the CPN Tools system,

which makes it possible to increase the stability of an automatic control system at the design stage without unnecessary costs. The usefulness of the presented analysis methodology when applied in distributed network expert systems, as well as in mass user service systems, is substantiated.

4. An integrated modification of the FCPN has been developed, in which the membership functions of the terms of the linguistic variable are applied to markers in the role of color, fuzzy conditions of existence are inserted into the arcs depending on the values of the linguistic variable, which provides a new qualitative nature of the connection between the structural elements of the network. In the presented FCPN, in parallel with the expansion of modeling capabilities, the reduction of the model space is also justified, which is a significant task in the theory of PN. Using FCPN, an automation model for adaptive fuzzy control of water pumps has been developed according to the water levels in the pump well.

5. Algorithms for the functioning of a combined modified FPN and SPN have been developed. The combined FPN makes it possible to model fuzzy production rules, the main parts of which are presented in the form of structural elements of the model, and the SPN is provided for the convenience of solving specific problems of modeling complex DS with probabilistic properties. It is substantiated that the presented modifications are a combination of three types of FPN and SPN, respectively, and have the advantages of all three. A fuzzy model of the control system of a production module in the form of FPN a master plan has been developed, a computer implementation of the model has been carried out, and an analysis has been performed.

6. An original hybrid approach to modeling intelligent control has been developed by creating a theory and methodology for the development of functional hybrid models of systems using an integrated FCPN for discrete processes, a fuzzy logical inference method for continuous processes and modern software and tool modeling systems CPN Tools and MATLAB. The developed hybrid method is characterized by parallel interpretation of discrete and

continuous processes, compactness of the model space, implementation of adaptive behavior, and software flexibility.

7. A model of fuzzy control of a water pump motor has been developed for more accurate and smooth speed control within load limits according to water consumption modes, where a hybrid modeling approach using FCPN is implemented. The developed model increases the adaptability of the system, which ensures economical water consumption, energy consumption compared to management using traditional methods, and also reduces carbon dioxide emissions, which have a dangerous effect on the environment.

8. A methodology for constructing a PN simulating a FA is presented, based on converting tables of transitions and outputs of the FA into a matrix of input and output incidents of the PN. Theorems proposing formulas for determining the elements of the incidence matrices of the PN of a simulating FA have been put forward and proven. It is shown that when transforming a FA into a PN, the personal properties of all structural elements are preserved and, accordingly, the PN takes on a certain extended modification, including a fuzzy one. An algorithm for automating the conversion has been developed, and a software implementation of the algorithm has been carried out in the C++ programming system. The significance of the proposed method for converting a PN into a FA is substantiated in the development of an automated control system for complex DS having modules in the form of discrete systems designed using the FA.

9. The results obtained have theoretical significance - the development of the theoretical foundations of intelligent automatic control systems based on the developed generalized, integrated, combined extensions of the PN, the presented hybridization and the method of converting the FA into the PN. The results obtained, along with theoretical qualities, also have practical significance; the use of the developed approaches, methods and models can be effective in modeling and verification of controls at the design stage of FPS, in expert systems, in tasks of servicing mass users, in decomposition processes and control of discrete devices, in dispatch control systems

of complex diesel engines operating in an uncertain environment with a fuzzy nature, in particular in thermal, water distribution and oil production.

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