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ABSTRACT

of the dissertation for a degree of Doctor of Philosophy

DEVELOPMENT OF FUZZY CONTROL MODELS AND ALGORITHMS FOR PARALLEL PROCESSES

Speciality: 3338.01 – System analysis, control, and Information Processing (modeling and control)

Field of science: Technical sciences

Applicant: **Irada Samad Zeynalabdiyeva**

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The work was performed at Sumgayit State University.

Scientific supervisor:	Doctor of technical sciences, professor **Mahammad Aydın Ahmadov**
Official opponents:	Doctor of technical sciences, professor **Mahammad Nurmahammad Nuriyev**
	Doctor of technical sciences, professor **Alekber Aliaga Aliyev**
	Candidate of technical sciences, associate professor **Nizami Duman Jafarov**

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Chairman of the Dissertation council:	Correspondent member of ANAS, Doctor of Technical Sciences, professor **Rafig Aziz Aliyev**
Scientific secretary of the Dissertation council:	doctor of philosophy İn Technical sciences, Assosiate professor **Akif Vali Alizadeh**
Chairman of the scientific seminar:	Doctor of technical sciences, professor **Tarlan Samad Abdullayev**

İMZANI TƏSDİQ EDİRƏM
ADNSU-nun Elmi katibi
dosent N.Əliyeva

GENERAL CHARACTERISTICS OF THE WORK

Relevance and Degree of Development of the Topic. The design and application of flexible manufacturing systems (FMS) that ensure the management of flexible manufacturing modules (FMM), created with the user, including new automation tools (industrial and intelligent robots, automatically controlled transport and warehouse systems, lifting-positioning manipulators, numerically controlled machines and equipment, etc.), and their complex management following the principles of asynchrony and parallelism, is one of the main promising scientific directions in the automation of production areas.

The design of machining centers oriented towards ensuring the operation of mechatronic devices (MD) and possessing high precision was of great importance for the implementation of FMM. Research indicates that due to various factors such as fluctuations in the power supply network, disruptions in environmental parameters like temperature, and others machining stages in MDs were prone to inaccuracies and failures. The analysis of the current state of the problem indicates that complex dynamic systems with a discrete nature should be modeled and studied as a set of interacting asynchronous automata. In this context, Petri nets (PN), a universal mathematical tool for describing cause-effect relationships, are widely applied. Using PN, objects can be modeled in the form of both static and dynamic models, allowing for in-depth investigation. Another advantage of PN is that the analysis of the key properties characterizing the network can be performed externally through computer experiments.

The analysis of complex systems operating under uncertainty shows that their modeling and investigation have both probabilistic and fuzzy (FS) characteristics, which in turn stimulates the creation of new designs. FMS must operate in an operational control mode to achieve the final goal within a specified time interval. Therefore, integrating two control technologies fuzzy logic (FL) and operational control methods into the management system of FMS is considered an efficient approach. From this perspective, the dissertation topic is highly relevant.

The object and subject of the research. The research object in the dissertation is mechanical processing production modules operating with the principle of parallelism in various types of situations. The work involves the modeling, study, and management of parallel-functioning production modules using extensions and modified constructions of Petri nets (PN), as well as the development of models and algorithms for their management.

Aim and Objectives of the Research. The aim of the dissertation is to investigate, model, and manage a FMS composed of parallel functioning FMMs in mechanical processing using the application of temporal, fuzzy, and C_f type fuzzy PN. The work involves the development of models and algorithms for the management of these systems.

Research Methods. In order to achieve the set goal, Petri net theory, graph theory, fuzzy set theory, mathematical modeling theories, and methods of the production rules concept have been used. To achieve this goal, the following problems to be solved have been identified in the dissertation.

Main clauses defended.

✓ Modeling, research, and development of control models in the form of extensions of Petri nets for parallel-operating production modules;

✓ Development of a management model for an automated complex consisting of parallel modules along a single route using temporal Petri nets (TPN);

✓ Justification for selecting fuzzy Petri nets (FPN) as the modeling tool, including the development of transition execution rules and algorithms for calculating structural elements;

✓ Development of FL management models for processing centers with two and three parallel modules in mechanical processing;

✓ Development of rules for transition execution and changes in the dynamic state of FPN;

✓ Description of parallel processes using fuzzy production rules (FPR) and development of an FPR base for controlling cassette conveyors in mechanical processing production;

✓ Development of a modified C_f type FPN model for controlling cassette conveyors in mechanical processing.

✓ Development of software for managing parallel-functioning FMMs in mechanical processing production systems.

Scientific innovations:

✓ A structural-kinematic scheme for an automated complex consisting of parallel modules along a single route has been proposed. Considering that the functional and cause-effect relationships of the elements are characterized by uncertain parameters, a management model in the form of temporal Petri nets (TPN) has been developed.

- ✓ In the example of the structural-kinematic diagram of the machining centers operating in the mechanical processing process, a fuzzy production model is described in the form of a FPN, and a control model for parallel-operating production modules is developed in the form of a modified FPN.
- ✓ The rules for executing the transitions of the FPN and the algorithm for calculating the structural elements have been developed. By applying this algorithm, control models for an automated complex consisting of parallel-operating mechanical processing production systems with two and three flexible production modules have been developed in the form of a modified FPN.
- ✓ The description of parallel-functioning processes using FPR has been analyzed. The feasibility and accuracy of using management models and algorithms developed based on the specification and verification of software for modeling discrete objects have been justified, using modified FPN.

Theoretical and practical significance and application of the results:

The theoretical and practical significance of the dissertation lies in the fact that the obtained scientific-practical results, proposed approaches, algorithms, and developed management models can be used in the design of FMS composed of parallel-functioning FMMs in mechanical processing, artificial intelligence technology, control systems, and the modeling and study of dynamically related parallel processes operating under complex and uncertain conditions.

Approval and application: Applied Problems of Mathematics and New Information Technologies, III Republican Scientific Conference (Sumgait, December 15-16, 2016); IV National Scientific-Practical Conference, Instrumentation and Automated Electric Drive in the Fuel and Energy Complex and Housing and Utilities Sector, Kazan State Energy University, Russia (Kazan, December 6-7, 2018); International Scientific Conference, Science, Technology, Production, Ufa State Petroleum Technological University, Russia, Salavat (Ufa, May 22, 2017); I Republican Conference on "Actual Scientific-Practical Problems of Software Engineering," Baku: Institute of Information Technology (Baku, May 17, 2017); Achievements and Prospects in Information Systems and Technologies: International Scientific Conference (Sumgait, November 15-16, 2018); XXI, XXII, XXIII Republican Scientific Conferences of Doctoral Students and Young Researchers (Baku, 2017, 2018, 2019); II International Scientific Conference on Achievements and Prospects in Information Systems and Technologies (Sumgait, July 9-10, 2020); Applied Problems of Mathematics and New Information Technologies, IV Republican Scientific Conference (Sumgait, December 9-10, 2021); The 8th International Conference on Control and Optimization with Industrial Applications (COIA 2022) (Baku, August 24-26, 2022); IECHCI 2022, International Eastern Conference on Human-Computer Interaction (Nakhchivan, September 9-10, 2022).

The name of the institution where the dissertation work was performed.

The work was carried out at Sumgayit State University. I express my gratitude to professor V.A. Mustafayev of the Informatics Department at SSU for his valuable scientific advice during the implementation of the research for this dissertation.

The scope and structure of the dissertation work. The dissertation consists of an introduction, four chapters, main conclusions, a list of 112 references, appendices, and a list of abbreviations. The total volume of the work is 128 pages, including 6 tables, 19 figures, and 179,084 characters: Introduction–24,100 characters, Chapter 1–47,790 characters, Chapter 2–42,709 characters, Chapter 3–47,621 characters, Chapter 4–14,680 characters, onclusion Results– 2,184 characters.

MAIN CONTENT OF THE WORK

In the introduction, the relevance of the topic and the conducted research is substantiated. The objectives and directions of the research are identified, along with the research object and subject, research methods, key theses presented for defense, scientific innovations, and practical significance of the research results. Additionally, the approbation of the work, the volume, and the structure of the dissertation are presented.

Chapter One. The modern state of modeling and control of parallel operating production modules is analyzed based on literature sources and practical experience. The investigation covers the problems of controlling technical systems operating under uncertainty and fuzziness. The Petri Net, a mathematical apparatus widely used for studying discrete systems, is considered an adequate model for representing cause-effect relationships. Additionally, the feasibility of implementing the principles of asynchrony and parallelism in the construction of PN ensures the modeling and analysis of distributed processes of various characteristics[1].

Experience shows that the use of traditional methods in the mathematical formulation of control problems in the application of a computer's operational control system is accompanied by certain difficulties. This is due to the rigidity of the model, i.e., the complexity of structural modifications of its elements and insufficient invariance to external distortive influences, resulting in a low degree of conformity to the real system. To address these issues, developing new approaches, particularly the application of various modifications of PN theory, becomes a relevant necessity.

In the **second chapter**, the development of control models for parallel operating production modules in the form of PN extensions is addressed. For this purpose, the study examines the development of modified PN-based fuzzy control models for a system consisting of parallel modules along a single route, two parallel operating production modules in a mechanical processing system, and three parallel operating Flexible Manufacturing Modules (FMM).

Development of a control model for an automated complex consisting of parallel modules along a single route

The automated complex, consisting of parallel-operating FMM, includes (Figure 1): three FMMs, each module comprising: a device (D), an industrial robot (IR), 2 storage units: S1,S3,S5-for unprocessed parts; S2,S4,S6- for processed parts; two transport manipulators (TM); storage for unprocessed parts (UPS); storage for processed finished parts (FPS); a distributing assembly robot (DAR); and an automated warehouse (AW).

[1] Ahmadov M.A., Zeynalabdiyeva İ.S. Analysis of the Current State of the Methods for Modeling Parallel-Operating Production Modules. // Sumgayit: Sumgayit State University, *Scientific News: Natural and Technical Sciences Section*, 2019, Volume 19, Issue 2, pp. 66-71.

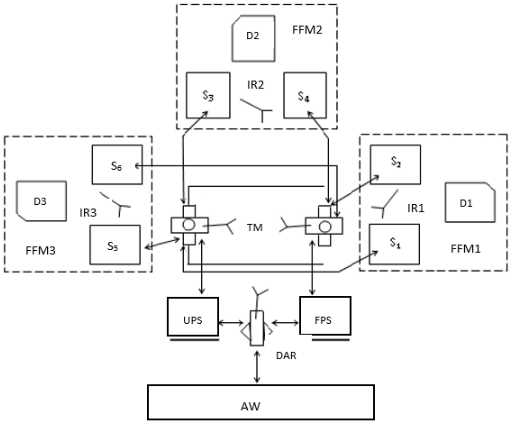

Figure 1. Structural kinematic scheme of the automated complex

Depending on the initial marker value, the connection between the selected module and its preceding and following modules is established through storage units. Thus, the process is carried out along a single route: unprocessed parts are placed in the input storage unit and wait for processing; if Device 1 is empty, it is loaded; the parts are processed, and then unloaded; next, Device 2 is loaded; after processing, Device 2 is unloaded, and then Device 3 is loaded; after processing, Device 3 is unloaded. Thus, the cycle repeats.

The control model of an automated complex consisting of parallel working Flexible Manufacturing Systems (FMS) is described in the form of a timed Petri net (TPN).

Set of Places: P_1 **:** the Transport Manipulator (TM) is at the Ready ; Workpiece Storage (RWS) position, and the gripper is closed. P_2: TM unloads the workpiece into the Processed Workpiece Storage (PWS). P_3: TM moves toward the RWS position. P_4: TM is at the RWS position, and the gripper is open. P_5: TM picks up an unprocessed workpiece from the RWS. P_6: TM moves towards the input storage of FMS1, and the gripper is closed. P_7: TM is at the input storage position of FMS1, and the gripper is closed. P_8: The RWS is empty. P_9: There is a workpiece in the RWS. P_{10}: The PWS is empty. P_{11}: There is a workpiece in the PWS. P_{12}: The Distribution Assembling Robot (DAR) moves toward the RWS position. P_{13}: DAR picks up a workpiece from the RWS. P_{14}: DAR places the finished workpiece into the AA storage and is loaded with an unprocessed workpiece. P_{16}: DAR is at the PWS position, and the gripper is closed. P_{17}: DAR places the workpiece into the PWS. P_{18}: DAR moves toward the RWS, and the gripper is open.

Set of Transitions: t_1: TM begins to unload the processed workpiece into the RWS. t_2: The unloading process of TM is complete. t_3: TM is in the loading position of the PWS. t_4: TM begins loading unprocessed workpieces from the PWS. t_5:The loading process of TM from the PWS is complete. t_6: TM is in the loading position of the FMS. t_7: The loading process of DAR at the PWS is complete. t_8: DAR is in the unloading position of the RWS. t_9: DAR begins the unloading process at the RWS. t_{10}: The unloading process of DAR at the RWS is complete. t_{11}: DAR is in the loading position of the PWS. t_{12}: DAR begins the loading process from the PWS.

The trajectory of the permissible transition sequence of the network, with the initial marking vector

$\mu_0 = (1001010101000 1101)$ has been found as:

$$\tau = (t_1\ t_2\ t_3\ t_4\ t_5\ t_6\ t_7\ t_4\ t_5\ t_7\ t_{12})$$

The t_1 transition is executed at τ=4 seconds, resulting in a new marking vector $\mu_1 = (01010100110001100)$; the t_2 transition is executed at $\tau = 7$ seconds, resulting in a new marking vector $\mu_2 = (00110100110001100)$; the t_3 transition is executed at $\tau = 9$ seconds, resulting in a new marking vector $\mu_3 = (00020100110001100)$; the t_4 transition is executed at $\tau = 12$ seconds, resulting in a new marking vector $\mu_4 = (00011100101001100)$; the t_5 transition is executed at $\tau = 15$ seconds, resulting in a new marking vector $\mu_5 = (00010110101001100)$; the t_6 transition is executed at $\tau = 17$ seconds, resulting in a new marking vector $\mu_6 = (00010020101001100)$; the t_7 transition is executed at $\tau = 19$ seconds, resulting in a new marking vector $\mu_7 = (00010020110101100)$; the t_4 transition is executed at $\tau = 22$ seconds, resulting in a new marking vector $\mu_8 = (00001020101101100)$; the t_5 transition is executed at $\tau = 25$ seconds, resulting in a new marking vector $\mu_9 =$

(00000030101101100); the t_7 transition is executed at $\tau = 27$ seconds, resulting in a new marking vector $\mu_{10} =$ (00000030110201100); the t_{12} transition is executed at $\tau = 30$ seconds, resulting in a new marking vector $\mu_{11} =$ (00000030100201101);

The operation duration has been completed.

The input and output incidence functions of the control model for an automated complex consisting of three production modules designed as a TPN have been defined. The structure of the control model in the form of a TPN has been established, and the sequence of transitions for the network has been determined. A graph-scheme of the control model for the automated complex along a specific route has been constructed (Figure 2).

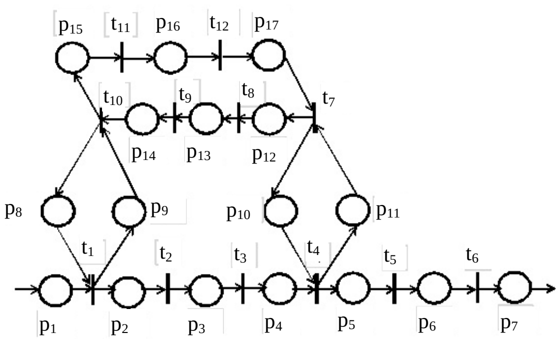

Figure 2. Graph-Scheme of the Control Model for the Automated Complex Along a Specific Route

The fuzzy control model of parallel operating production modules consisting of two modules in the mechanical processing process.

In uncertain conditions, the control model of parallel operating FMS in a mechanical processing production system is described as a Fuzzy Petri Net (FPN). For this purpose, the dissertation develops rules for the execution of transitions in the FPN and an algorithm for calculating the structural elements.

The figure shows: 1-Device 1 performing the first operation on the workpiece; 2-Device 2 performing the first operation on the workpiece; 3-Input storage of Device 1; 4- Input storage of Device 2; 5-Output storage of Device 1; 6-Output storage of Device 2; 7-Industrial Robot 1 (IR1) loading unprocessed workpieces into the input buffer of Device 1 and Device 2; 8- Industrial Robot 2 (IR2) unloading processed workpieces from the output buffer of Device 1 and Device 2

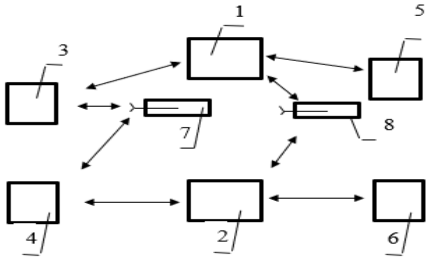

Figure 3. Structural kinematic diagram of parallel operating processing devices

The production system of the module processing the workpiece is organized according to the following rules[2]:

Rule 1: If there is an unprocessed workpiece in the input storage of Device 1, and IR1 is idle, and Device 1 is not performing the first operation on the workpiece, then IR1's arm moves left, picks up the workpiece, and loads Device 1.

Rule 2: If there is an unprocessed workpiece in the input storage of Device 2, and IR1 is idle, and Device 2 is not performing the second operation on the workpiece, then IR1's arm moves right, picks up the workpiece, and loads Device 2.

Rule 3: If there is a workpiece in the input buffer of Device 1, then Device 1 performs the first operation on the workpiece.

Rule 4: If there is a workpiece in the input buffer of Device 2, then Device 2 performs the second operation on the workpiece.

Rule 5: If there is a processed workpiece in the output buffer of Device 1, the output storage of Device 1 is empty, and SR2 is idle,

[2] Ataev G.N., Zeynalabdiyeva İ.S. Decision-Making Model for the Control of Parallel-Operating Processing Devices. // Sumgayit: Sumgayit State University, *Scientific News: Natural and Technical Sciences Section*, 2022, Volume 22, Issue 2, pp. 64-69.

then SR2's arm moves left, picks up the workpiece, and unloads Device 1.

Rule 6: If there is a processed workpiece in the output buffer of Device 2, the output storage of Device 2 is empty, and SR2 is idle, then SR2's arm moves right, picks up the workpiece, and unloads Device 2.

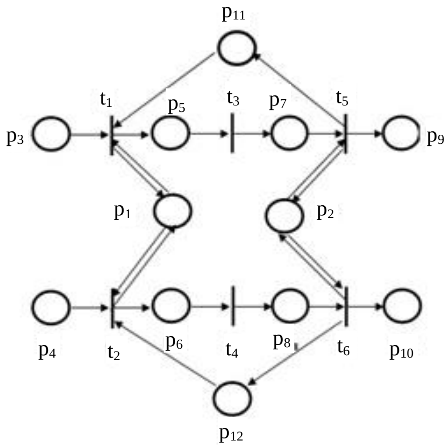

Figure 4. Graph-scheme of parallel operating processing units in the form of a Petri net

In the graph-diagram of parallel operating processing units in a mechanical production system, the set of positions is described as follows (Figure 4): P_1 - IR1, which provides loading for Device 1 and Device 2.; P_2 - IR2, which provides loading for Device 1 and Device 2; P_3 - Input Storage of Device 1: Storage for unprocessed workpieces for Device 1; P_4 - Input Storage of Device 2: Storage for unprocessed workpieces for Device 2; P_5 - Input Buffer of Device 1: Number of unprocessed workpieces in the input buffer of Device 1; P_6 - Input Buffer of Device 2**:** Number of unprocessed workpieces in the input buffer of Device 2; P_7 - Output Buffer of Device 1: Number of processed workpieces in the output buffer of Device 1.; P_8 - Output

Buffer of Device 2**:** Number of processed workpieces in the output buffer of Device 2; P_9 - Output Storage of Device 1: Storage for processed workpieces of Device 1.; P_{10} - Output Storage of Device 2**:** Storage for processed workpieces of Device 2.; P_{11} - Device 1: Device performing the first operation on unprocessed workpieces; P_{12} - Device 2: Device performing the second operation on unprocessed workpieces.

The events occurring in the module with parallel operating processing units are described in the form of the following transitions: t_1 - Industrial Robot 1 (IR1) ensures the loading of the input buffer of Processing Unit 1; t_2 - : t_1 - Industrial Robot 1 (IR1) ensures the loading of the input buffer of Processing Unit 2; t_3 - Processing Unit1 performs the first operation on the unprocessed workpiece.; t_4 - Processing Unit2 performs the second operation on the unprocessed workpiece.; t_5 - Industrial Robot 2 (IR2) performs the unloading operation at the output buffer of Device 1; t_6 - Industrial Robot 2 (IR2) performs the unloading operation at the output buffer of Device 2.

The incidence function of the set of places and transitions in the network is described in the form of $\overset{-}{C}(6,12)$ and $\overset{+}{C}(6,12)$ matrices:

$$\overset{-}{C}(6,12)=\begin{vmatrix} 1&0&1&0&0&0&0&0&0&0&1&0\\ 1&0&0&1&0&0&0&0&0&0&0&1\\ 0&0&0&0&1&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0&0&0&0&0\\ 0&1&0&0&0&0&1&0&0&0&0&0\\ 0&1&0&0&0&0&0&1&0&0&0&0 \end{vmatrix} \quad \overset{+}{C}(6,12)=\begin{vmatrix} 1&0&0&0&1&0&0&0&0&0&0&0\\ 1&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&0&1&0&0&0&0\\ 0&1&0&0&0&0&0&0&0&1&1&0\\ 0&1&0&0&0&0&0&0&0&1&0&1 \end{vmatrix}$$

The elements of the incidence matrix of the network are calculated using the $c_{i\,j}=\overset{+}{C}_{ij}-\overset{-}{C}_{ij}$ $\quad i=1,\overline{6};\ j=1,\overline{12}$ formula:

$$C_{ij}=\begin{vmatrix} 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 1 \end{vmatrix}$$

The initial state of the module with parallel operating processing units is given by the following vectors:

$$\mu(0,1)=(0.200,0.400);\ \mu(0,2)=(0.300,0.500);$$
$$\mu(0,3)=(0.500,0.700);\ \mu(0,4)=(1.000,0.900);$$
$$\mu(0,5)=(0.500,0.500);\ \mu(0,6)=(1.000,0.900);$$
$$\mu(0,7)=(1.000,0.900);\ \mu(0,8)=(0.500,0.500);$$
$$\mu(0,9)=(0.400,0.600);\ \mu(0,10)=(0.600,0.400);$$
$$\mu(0,11)=(1.000,0.900);\mu(0,12)=(0.500,0.500).$$

The new marking matrices obtained during the execution of the transitions are as follows:

$$\mu_0=\begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.5 & 0.7 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 1.0 & 0.9 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \end{Vmatrix}\quad \mu_1=\begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 1.0 & 0.9 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 1.0 & 0.0 \\ 0.5 & 0.5 \end{Vmatrix}\quad \mu_2=\begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 1.0 & 0.9 \\ 1.0 & 0.9 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 1.0 & 0.0 \\ 0.5 & 0.5 \end{Vmatrix}\quad \mu_3=\begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.0 \\ 0.5 & 0.5 \\ 0.6 & 0.6 \\ 0.6 & 0.6 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 1.0 & 0.0 \\ 0.5 & 0.5 \end{Vmatrix}$$

$$\mu_4 = \begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.0 \\ 0.5 & 0.0 \\ 0.6 & 0.0 \\ 0.6 & 0.6 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 1.0 & 0.0 \\ 0.5 & 0.0 \end{Vmatrix} \quad \mu_5 = \begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.0 \\ 0.5 & 0.0 \\ 0.6 & 0.0 \\ 0.6 & 0.0 \\ 0.5 & 0.5 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.5 & 0.0 \end{Vmatrix} \quad \mu_6 = \begin{Vmatrix} 0.2 & 0.4 \\ 0.3 & 0.5 \\ 0.7 & 0.0 \\ 1.0 & 0.0 \\ 0.5 & 0.0 \\ 0.6 & 0.0 \\ 0.6 & 0.0 \\ 0.5 & 0.0 \\ 0.4 & 0.6 \\ 0.6 & 0.4 \\ 0.6 & 0.4 \\ 0.5 & 0.4 \end{Vmatrix}$$

As a result of the computer simulation, the sequence of transitions from the initial marking is $\delta = (t_1 t_2 t_3 t_4 t_5 t_6)$.

Transition t_1 is executed, and a new marking matrix μ_1 is obtained, transition t_2 is executed, and a new marking matrix μ_2 is obtained, transition t_3 is executed, and a new marking matrix μ_3 is obtained, transition t_4 is executed, and a new marking matrix μ_4 obtained, transition t_5 is executed, and a new marking matrix μ_5 obtained, transition t_6 is executed, and a new marking matrix μ_6 obtained.

Fuzzy control model of parallel operating flexible manufacturing modules in a mechanical processing production system

Let's examine the development of the control model for a parallel operating flexible manufacturing module consisting of three modules. In a flexible manufacturing system (FMS), each FMM consists of an Industrial Robot (IR), an individual input buffer, processing units that perform a specific type of processing on semifinished products, and an output buffer for the processed products. Each module processes one type of part. The semifinished product is placed in the input buffer and awaits processing. The empty device picks it up and performs the processing. After the processing is completed, the processed part is placed in the output buffer.

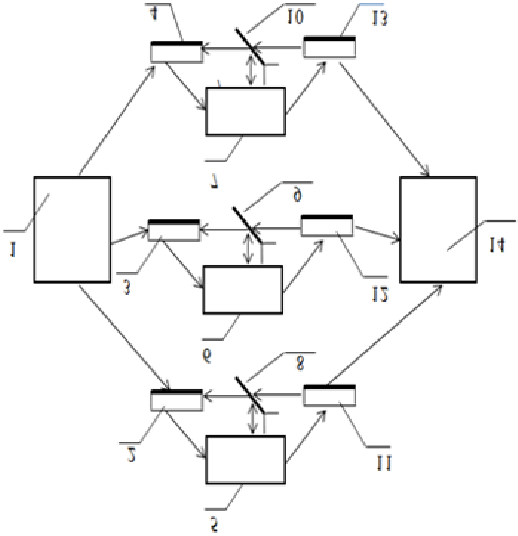

Figure 5. Structural diagram of the parallel operating processing center

The structure of the parallel operating processing devices is shown in Fig. 5: 1 - semifinished product warehouse; 2, 3, 4 - input buffers of Device 1, Device 2, Device 3, respectively; 5, 6, 7 - Device 1, Device 2, Device 3, respectively; 8, 9, 10 - IR1, IR2, IR3, respectively; 11, 12, 13 - output buffers of Device 1, Device 2, Device 3, respectively; 14 - finished product warehouse[3].

The dynamic states of the modules in the graph-scheme of the parallel working FMM in a mechanical processing flexible manufacturing system are described by the following places (Fig. 6).

P_1- warehouse of semi-finished products; P_2 , P_3 , P_4 – input buffers of device1, device2, device3. P_5 , P_6 , P_7 – signals denying the loading of device1, device2, device3. P_8, P_9, P_{10} – Industrial robots (SR1, SR2, SR3) that ensure the loading and unloading of device1,

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[3]Ataev G.N., Zeynalabdiyeva İ.S. Control Model for Parallel-Operating Production Modules in a Machining System. // *Mathematical Methods in Engineering and Technologies (MMET)*, Saratov State Technical University, Saratov, Russia, 2017, Volume 9, pp. 111-116.

device2, device3 ; P_{11}, P_{12}, P_{13} – device1, device2, device3 performing operations on semi-finished products, P_{14}, P_{15}, P_{16} – output buffer of device1, device2, device3.; P_{17} - finished goods warehouse.

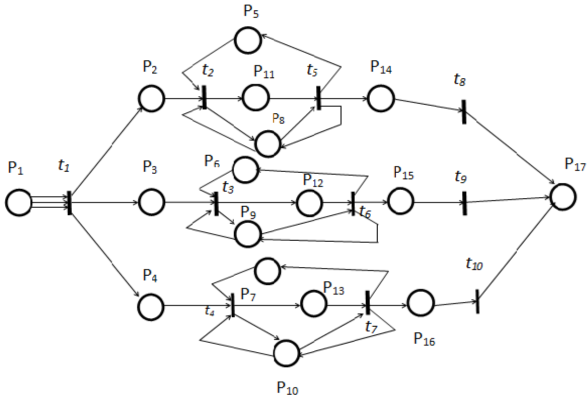

Figure 6. Schematic diagram of parallel operating flexible manufacturing modules

Possible events in parallel operating Flexible Manufacturing Modules are described by the following transitions: t_1 – Transfer of the semi-finished product from the warehouse to the input positions of device1, device2, device3.; t_2, t_3, t_4 – Loading process of device1, device2, device3. t_5, t_6, t_7 – Unloading of the load from device1, device2, device3. t_8, t_9, t_{10} – Transfer of processed parts from the input of device1, device2, device3 to the finished goods warehouse.

One of the advantages FPN is the effective representation of rules that are part of fuzzy production rules (FPR) as elements of the network, and the possibility of deriving logical conclusions based on the Fuzzy Set Theory. In this case, the positions and transitions of the FPN are interpreted as follows: 'Rule: If A is true, then B is true.'

The execution of transitions and the change in the dynamic state of the fuzzy Petri net are determined by the following rules[4]:

[4] Mustafayev V.A., Zeynalabdıyeva İ.S., O.Ja. Kravets Control model of parallel functioning production modules as fuzzy petri nets // Journal of Physics: Conference Series. Published under licence by IOP Publishing Ltd Volume 2094 022003-2021 doi:10.1088/1742-6596/2094/2/022003

Rule 1: If there is a semi-finished product in the warehouse and there is no semi-finished product in the input buffers of device 1, device 2, and device 3, then the process of transferring the semi-finished product from the warehouse to the input buffers of device 1, device 2, and device 3 should be carried out.

Rule 2: If there is a semi-finished product in the input buffer of device 1, and device 1 is free, and SR1 is free, then the loading process of device 1 should be carried out.

Rule 3: If there is a semi-finished product in the input buffer of device 2, and device 2 is free, and SR2 is free, then the loading process of device 2 should be carried out.

Rule 4: If there is a semi-finished product in the input buffer of device 3, and device 3 is free, and SR3 is free, then the loading process of device 3 should be carried out.

Rule 5: If the operation performed by device 1 on the semi-finished product is completed, and SR1 is free, then the unloading process of device 1 should be carried out.

Rule 6: If the operation performed by device 2 on the semi-finished product is completed, and SR2 is free, then the unloading process of device 2 should be carried out.

Rule 7: If the operation performed by device 3 on the semi-finished product is completed, and SR3 is free, then the unloading process of device 3 should be carried out.

Rule 8: If there is a processed part in the output buffer of device 1, and SR1 is free, then the process of transferring the processed part from the output buffer of device 1 to the finished goods warehouse should be carried out.

Rule 9: If there is a processed part in the output buffer of device 2, and SR2 is free, then the process of transferring the processed part from the output buffer of device 2 to the finished goods warehouse should be carried out.

Rule 10: If there is a processed part in the output buffer of device 3, and SR3 is free, then the process of transferring the processed part from the output buffer of device 3 to the finished goods warehouse should be carried out.

The incidence functions of the set of positions and transitions are described by the following matrices:

$$F(10,17)=\begin{vmatrix}3&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\0&1&0&0&1&0&0&1&0&0&0&0&0&0&0&0&0\\0&0&1&0&0&1&0&0&1&0&0&0&0&0&0&0&0\\0&0&0&1&0&0&1&0&0&1&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&1&0&0&1&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&1&0&0&1&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&1&0&0&1&0&0&0&0\\0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0\\0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0\end{vmatrix}$$

$$H(17,10)=\begin{vmatrix}0&0&0&0&0&0&0&0&0&0\\1&0&0&0&0&0&0&0&0&0\\1&0&0&0&0&0&0&0&0&0\\1&0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&1&0&0&0\\0&1&0&0&1&0&0&0&0&0\\0&0&1&0&0&1&0&0&0&0\\0&0&0&1&0&0&1&0&0&0\\0&1&0&0&0&0&0&0&0&0\\0&0&1&0&0&0&0&0&0&0\\0&0&0&1&0&0&0&0&0&0\\0&0&0&0&1&0&0&0&0&0\\0&0&0&0&0&1&0&0&0&0\\0&0&0&0&0&0&1&0&0&0\\0&0&0&0&0&0&0&1&1&1\end{vmatrix}$$

The incidence matrix defining the structure of the model is as follows

$$D(10,17)=\begin{vmatrix}-3&1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0\\0&-1&0&0&-1&0&0&0&0&0&1&0&0&0&0&0&0\\0&0&-1&0&0&-1&0&0&0&0&0&1&0&0&0&0&0\\0&0&0&-1&0&0&0&-1&0&0&0&0&1&0&0&0&0\\0&0&0&0&0&0&0&0&0&0&-1&0&0&1&0&0&0\\0&0&0&0&0&0&0&0&0&0&0&-1&0&0&1&0&0\\0&0&0&0&0&0&1&0&0&0&0&0&-1&0&0&1&0\\0&0&0&0&0&0&0&0&0&0&0&0&0&-1&0&0&1\\0&0&0&0&0&0&0&0&0&0&0&0&0&0&-1&0&1\\0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&-1&1\end{vmatrix}$$

From the computer experiment, a trajectory of transition sequences $\delta=(t_1,t_3,t_4,t_5,t_6,t_7,t_8,t_9,t_{10},t_{10})$ was obtained starting from the initial markin μ_0

As a result of the execution of the corresponding transitions, new markings are obtained. The sequence of the initial marking matrix μ_0 and the new marking matrices obtained during the execution of the transitions is as follows:

The transition is executed t_1, a new marking matrix μ_1 is obtained, the transition is executed t_3, a new marking matrix μ_2 is obtained,the transition is executed t_4, a new marking matrix μ_3 is obtained,the transition is executed t_5, a new marking matrix μ_5 is obtained,the transition is executed t_6, a new marking matrix μ_7 is obtained, the transition is executed t_7, a new marking matrix μ_{10} is obtained, the transition is executed t_8 , a new marking matrix μ_{13} is obtained, the transition is executed t_9 , a new marking matrix μ_{16} is obtained, the transition is executed t_{10} , a new marking matrix μ_{19} is obtained, the transition is executed t_{10} , a new marking matrix μ_{21} is obtained.

Based on the initial data provided above, the computer simulation of the network was carried out, resulting in the set of states of the network. The service trajectory of parallel operating production modules in mechanical processing manufacturing systems was determined. During the simulation process of the model, an optimal trajectory was selected, excluding random delays. It has been demonstrated that the execution of transitions based on the accepted rules fully represents the operation and dynamics of the fuzzy Petri net.

In the **third chapter**, issues related to decision-making and the development of network models for controlling cassette conveyors in mechanical processing manufacturing systems are discussed.

The description of parallel processes using fuzzy production rules is provided.

In mechanical processing manufacturing, the following issues are addressed for the development of a fuzzy inference and decision-making model for controlling cassette conveyors: defining input and output linguistic variables and their term sets for creating a fuzzy production rules base; fuzzification of linguistic variables; performing aggregation of input linguistic variables and determining their membership degrees; and activation of results based on fuzzy production rules and defuzzification of the output variable.

To achieve this, the issue of describing parallel processes using fuzzy production rules has been considered. It has been shown that to form the rule base of a fuzzy production system, the input and output linguistic variables of the base must be defined. The input linguistic variables are formally determined by the following variables: the loading coefficient of the input buffer of the processing device and the movement speed of the cassette conveyor. For fuzzification of the rule base for decision-making in controlling the cassette conveyor, a trapezoidal membership function is used. The membership function for trapezoidal fuzzy intervals (TFI) is an interval defined by the f_T trapezoidal function.

f_T – The trapezoidal function is described by the following expression:

$$f_T(x; a, b, \alpha, \beta) = \begin{cases} 0, x \leq \alpha \\ \dfrac{x-\alpha}{a-\alpha}, \alpha \leq x \leq a \\ 1, \quad a \leq x \leq b \\ \dfrac{\beta - x}{\beta - b}, b \leq x \leq \beta \\ 0, \quad \beta \leq x \end{cases}$$

Here a, b, α, β are parameters that take arbitrary real values and satisfy the condition $\alpha \leq a \leq b \leq \beta$

The following sets are used as the term sets for input linguistic variables:

TL1=(zero, close to zero, near negative to normal, normal, near positive to normal);

TL2= (minimum, middle, maximum).

The valve of the pneumomotor of the cassette conveyor is set as output linguistically variable. The following set is taken as the term set of the output linguistic variable:

TL3=(non-large right angle, large right angle, unchanged state, non-large left angle, large left angle);

As a result of the implementation of the fuzzification procedure for input and output linguistic variables, the fuzzy production rule base for controlling the cassette conveyor in mechanical processing manufacturing consists of the following rules[5]:

[5] Zeynalabdiyeva I.S., "Decision-making model for the control of cassette conveyor movement in mechanical processing production," Bulletin of the Ufa State Aviation

Rule 1: IF the loading factor of the inlet hopper of the processing unit is zero, close to zero [0, 0, 0.25, 1] , AND the moving speed of the cassette conveyor is minimum [0, 1.56, 3.15, 7.91] , THEN turn the valve of the pneumatic motor of the cassette conveyor to the right at a large angle [65, 75, 90, 90] ;

Rule 2: IF the loading factor of the inlet hopper of the processing unit is zero, close to zero [0, 0, 0.25, 1], AND the moving speed of the cassette conveyor is medium [2.88, 8.78, 11.9, 16.8], THEN turn the valve of the pneumatic motor of the cassette conveyor to the right at a large angle [65, 75, 90, 90] ;

Rule 3: IF the loading factor of the inlet hopper of the processing unit is zero, close to zero [0, 0, 0.25, 1], AND the moving speed of the cassette conveyor is maximum [11.98, 17.2, 20.8, 27.2], THEN turn the valve of the pneumatic motor of the cassette conveyor at a small right angle [44, 55, 65, 75] ;

Rule 4: IF the loading factor of the inlet hopper of the processing unit is close to negative normal [0.33, 1.5, 2, 2.5], AND the speed of the cassette conveyor is minimal [0, 1.56, 3.15, 7.91], THEN turn the valve of the pneumatic motor of the cassette conveyor at a small right angle [44, 55, 65, 75] ;

Rule 5: IF the loading factor of the inlet hopper of the processing unit is close to negative normal [0.33, 1.5, 2, 2.5], AND the speed of the cassette conveyor is medium [2.88, 8.78, 11.9, 16.8] THEN keep the valve of the pneumatic motor of the cassette conveyor unchanged [27.97, 37, 43, 55];

Rule 6: IF the loading factor of the inlet hopper of the processing unit is close to negative normal [0.33, 1.5, 2, 2.5], AND the speed of the cassette conveyor is maximum [11.98, 17.2, 20.8, 27.2], THEN turn the valve of the pneumatic motor of the cassette conveyor at a small left angle [9.286, 19.29, 29.29, 39.29];

Rule 7: IF the loading factor of the inlet hopper of the processing unit is close to positive normal [2.7, 3.06, 4, 4], AND the speed of

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Technical University, Republic of Bashkortostan, Ufa, Russia, Vol. 26, No. 2, 2022, pp. 126-133.

the cassette conveyor is minimal [0, 1.56, 3.15, 7.91], THEN turn the valve of the pneumatic motor of the cassette conveyor at a small left angle [9.286, 19.29, 29.29, 39.29];

Rule 8: IF the loading factor of the inlet hopper of the processing unit is close to positive normal [2.7, 3.06, 4, 4], AND the speed of the cassette conveyor is medium [2.88, 8.78, 11.9, 16.8] THEN turn the valve of the pneumatic motor of the cassette conveyor at a large left angle [0 , 0 , 10 , 23.21];

Rule 9: IF the loading factor of the inlet hopper of the processing unit is close to positive normal [2.7, 3.06, 4, 4], AND the speed of the cassette conveyor is maximum [11.98, 17.2, 20.8, 27.2], THEN turn the valve of the cassette conveyor pneumatic motor at a large left angle [0, 0, 10, 23.21].

Fuzzyfication of the Cassette Conveyor Control Rules

TL1: Input linguistic variable, the fuzzification of the load factor (LF) of the input buffer for the processing unit is carried out using trapezoidal fuzzy sets in the universe X=[0,4]:$\widetilde{L1_1}$ = [0, 0, 0.25, 1] Zero, close to zero ; $\widetilde{L1_2}$= [0.33, 1.5, 2, 2.5] Close to normal, negative*;* $\widetilde{L1_3} =$ = [1.8, 2.22, 2.63, 3.23] normal; $\widetilde{L1_4}$= [2.7, 3.06, 4, 4] Close to normal, positive. TL2: Input linguistic variable, the fuzzification of the conveyor speed (CS) is carried out using trapezoidal fuzzy sets in the universe Y=[0,20]: $\widetilde{L2_1}$ = [0, 1.56, 3.15, 7.91] minimum; $\widetilde{L2_2}$= [2.88, 8.78, 11.9, 16.8] medium*;* $\widetilde{L2_3}$ = [11.5, 15.1, 17.4, 20.1] maximum. L3: Output Linguistic Variable, the fuzzification of the valve (PV) turning angle of the cassette conveyor is carried out using trapezoidal fuzzy sets in the universe Z=[0,90]:$\widetilde{L3_1}$ = [9.286 19.29 29.29 39.29] Small left angle. $\widetilde{L3_2}$= [0 0 10 23.21] Large left angle. $\widetilde{L3_3}$ =[27.97,37,43,55] Unchanged position. $\widetilde{L3_4}$ = [44,55.65,75] Small right angle; $\widetilde{L3_5}$ =[65,75,90,90] Large right angle.

The corresponding fuzzy term sets for the TL1 input linguistic variable are defined as follows:

$$\widetilde{L1_1}\ (x) = \{(1/0),(1/0.2),(0.75/0.4),(0.53/0.6),(0.26/0.8),(0.133/0.9)\};$$

$$\widetilde{L1_2}(x) = \left\{\begin{matrix}(0/0.33),(0{,}743/1.2),(1/1.5),(1/1.9),(0.8/2.1),(0.4/2.3),\\(0/2.5)\end{matrix}\right\};$$

$$\widetilde{L1_3}(x) = \{(0/1.8),(1/2.3),(0.716/2.8),(0.216/3.1),(0.05/3.2),(0/3.23)\};$$

$$\widetilde{L1_4}(x) = \{(0/2.7),(0.277/2.8),(0.555/2.9),(0.833/3.0),(1/3.3),(1/3.6),$$

$(1/3.9)\}$.

The corresponding fuzzy term set of a fuzzy TL2 input linguistic variable is defined as follows:

$$\widetilde{L2}_1(y) = \{(0.320/0.5), (0,961/1.5), (1/2.5), (1/2.9), (0.716/4.5), (0.296/6.5), (0/7.9\,1)\};$$
$$\widetilde{L2}_2(y) = \{(0/2.88), (0.020/3), (0.359/5), (1/9), (1/10), (0.979/12), (0.163/16), (0/16.8)\};$$
$$\widetilde{L2}_3(y) = \{(0/11.5), (0.386/12), (1/14), (15), (0.812/16), (0.5/17), (0.187/18), (0/20.1)\}.$$

The corresponding fuzzy term set of a fuzzy TL3 input linguistic variable is defined as follows:

$$\widetilde{L3}_1(z) = \{(1/0), (1/6), (0.924/11), (0.545/16), (0.394/18), (0.091/22), (0.015/23), (0/23.21)\};$$
$$\widetilde{L3}_2(z) = \{(0/9.28), (0.3/12.28), (0.702/16), (1/20), (1/23.6), (0.83/31), (0.63/33), (0/39.28)\};$$
$$\widetilde{L3}_3(z) = \{(0/65), (0.47/70), (0.944/75), (1/80), (1/85), (1/90)\};$$
$$\widetilde{L3}_4(z) = \{(0/44), (0.545/50), (1/60), (1/65), (0.6/69), (0.2/73), (0/75)\};$$
$$\widetilde{L3}_5(z) = \{(0/27.98), (0.223/30), (1/38), (1/40), (0.916/44), (0.416/50), (0.25/52), (0/55)\}.$$

The membership function values of the linguistic variable term sets $\widetilde{L1}(x)$ and $\widetilde{L2}(y)$ are calculated for the input values x=3.1 and y=12.7

$\widetilde{L1}_1(x) = 0$; $\widetilde{L1}_2(x) = 0$; $\widetilde{L1}_3(x) = 0.213$; $\widetilde{L1}_4(x) = 1$;
$\widetilde{L2}_1(y) = 0$; $\widetilde{L2}_1(y) = 0.837$; $\widetilde{L2}_1(y) = 1$.

In a fuzzy inference system, the aggregation condition is performed by applying fuzzy implication to each production rule within the subsystem. Activation is the process of determining the degree of truth q_i (where $i = \overline{1,9}$) corresponding to each fuzzy production rule. For this purpose, the algebraic product of the truth degrees of the subconditions is calculated with respect to the weight coefficient of the corresponding rule. The membership function values of the linguistic variable term sets $\widetilde{L3}(z)$ are calculated for the output value z=49.

$\widetilde{L3}_1(z) = 0$; $\widetilde{L3}_2(z) = 0$; $\widetilde{L3}_3(z) = 0.5$;
$\widetilde{L3}_4(z) = 0.455$; $\widetilde{L3}_5(z) = 0$.

After defining the set $q_i(i = \overline{1,9})$, the membership function for the sub-set of each production rule p_i is determined using the fuzzy composition method.

$$\mu(P_i) = min\{q_i, \mu_{\widetilde{L3}}(x_i)\}, i = \overline{1,9}.$$

Here, $\mu_{\widetilde{L3}}(x_i)$ is the membership function of the term set of the output linguistic variable, and q_i represents the truth degrees of the subconditions of the fuzzy production rule:

$$\mu(p_3) = min\{q_1, \widetilde{L3}_4(50)\} = min\{0.455; 0.545\} = 0.455;$$
$$\mu(p_4) = min\{q_2, \widetilde{L3}_4(45)\} = min\{0.455; 0.09\} = 0.09;$$
$$\mu(p_5) = min\{q_3, \widetilde{L3}_3(31)\} = min\{0.5; 0.335\} = 0.335;$$
$$\mu(p_1) = \mu(p_2) = \mu(p_6) = \mu(p_7) = \mu(p_8) = \mu(p_9) = 0.$$
$$x = (50 \cdot 0.455 + 45 \cdot 0.09 + 31 \cdot 0.335)/(0 \cdot 455 + 0.09 + 0.335) = 42{,}25$$

The defuzzification procedure is considered complete when the quantitative values of each output linguistic variable result in final values expressed as real numbers.

The fuzzy logic inference mechanism for controlling the movement of the cassette conveyor in mechanical processing production is provided. Using the Fuzzy Logic Toolbox package in the MATLAB environment, the fuzzification of input and output linguistic variables has been implemented. By applying the Mamdani algorithm and using the center of gravity method, the quantitative values of the output linguistic variable have been obtained.

The network model of cassette conveyor control in mechanical processing production.

The control model of the cassette conveyor in the mechanical processing production system is described as a C_f type fuzzy Petri net. The modified C_f type FPN is described as follows:

$$C_f = (N_p, f, \lambda, \mu_0)$$

here :

- $N_p = (P, T, I, O)$ - it is a modified C_f type fuzzy Petri net (FPN).: $P = \{p_i\}, (i = \overline{1,n})$ -a finite set of fuzzy positions. $T\{t_i\}, (i = \overline{1,m})$ - a finite set of fuzzy transitions.; $I : P \times T \to (0,1)$ and $O : T \times P \to (0,1)$ - the input and output functions of the transitions are;
- $f = (f_1, f_2, ..., f_m)$ - the values of the membership function vector for the execution of the fuzzy transition are, for each $f_i \in [0,1], [\forall i \in (1,2,...N)]$, N is the set of natural numbers.

- $\lambda = (\lambda_1, \lambda_2, ..., \lambda_m)$ - The values of the excitation threshold vector for the execution of the transition are, for each $\lambda_i \in [0,1], [\forall i \in (1,2,..., N)]$;
- $\mu_0 = (\mu_1^0, \mu_2^0, ..., \mu_n^0)$ - it is the initial marking vector. Each element of this vector is determined by the value of the fuzzy membership function of a marker located in the corresponding position of the network, for each $\mu_i^0 \in [0,1], [\forall i \in (1,2,..., N)]$.

The current state vector of the modified C_f type FPN is defined, by the values of the membership function of a marker located at the corresponding position $\mu = (\mu_1, \mu_2, ..., \mu_n)$. The elements of this vector are determined by the value of the fuzzy membership function of a marker in the $(\mu_i \in [0,1])$ $p_i \in P$ -th position.

The transition of the modified C_f type FPN is enabled when the condition

$$min\{m_i\} \geq \lambda_k / \, [i \in (1,2, ..., N)] \wedge [I(p_i, t_k) > 0]$$

The set of places and transitions included in the structure of the C_f type FPN are described according to the rule base based on the production system created in paragraph 3.2. The structure of the C_f type FPN is defined as follows.

The set of positions:

P_1-the loading coefficient of the input hopper of the processing unit is near zero; P_2- the speed of the cassette conveyor is minimal; P_3- the valve of the pneumatic motor of the cassette conveyor is turned at a large right angle; P_4- the speed of the cassette conveyor is medium; P_5- the speed of the cassette conveyor is maximal;P_6-the valve of the pneumatic motor of the cassette conveyor is turned at a small right angle; P_7-the loading coefficient of the input hopper of the processing unit is negative, close to normal;P_8- the valve of the pneumatic motor of the cassette conveyor is kept in a constant position;P_{10}- the valve of the pneumatic motor of the cassette conveyor is turned at a small left angle; P_9- the loading coefficient of the input hopper of the processing unit is positive, close to normal;P_{11}- the valve of the pneumatic motor of the cassette conveyor is turned at a large left angle.

The set of transitions:

t_1- the input places of the transition according to Rule 1: P_1, P_2; $pred(t_1) = \{P_1, P_2\}$; t_1 the output place of the transition: P_3 ; $post(t_1) = \{P_3\}$; t_2- the input places of the transition according to Rule 2: P_1, P_4 ; $pred(t_2) = \{P_1, P_4\}$; t_2 - the output place of the transition: P_3; $post(t_2) = \{P_3\}$;t_3- the input places of the transition according to Rule 3: P_1, P_5; $pred(t_3) = \{P_1, P_5\}$; t_3 the output place of the transition: P_6 ; $post(t_3) = \{P_6\}$; t_4- the input places of the transition according to Rule 4: P_2, P_7 ; $pred(t_4) = \{P_2, P_7\}$; t_4 the output place of the transition: P_6; $post(t_4) = \{P_6\}$;t_5- the input places of the transition according to Rule 5: P_4, P_7; $pred(t_5) = \{P_4, P_7\}$; t_5 the output place of the transition: P_8; $post(t_5) = \{P_8\}$; t_6- the input places of the transition according to Rule 6: P_5, P_7 ; $pred(t_6) = \{P_5, P_7\}$; t_6 the output place of the transition: P_{10}; $post(t_6) = \{P_{10}\}$; t_7- the input places of the transition according to Rule 7: P_1, P_9; $pred(t_7) = \{P_1, P_9\}$; t_7 the output place of the transition: P_{10} ; $post(t_7) = \{P_{10}\}$; t_8- the input places of the transition according to Rule 8: P_4, P_9 ; $pred(t_8) = \{P_4, P_9\}$; t_8 the output place of the transition: P_{11}; $post(t_8) = \{P_{11}\}$; t_9- the input places of the transition according to Rule 9: P_5, P_9; $pred(t_9) = \{P_5, P_9\}$; t_9 the output place of the transition: P_{11}; $post(t_9) = \{P_{11}\}$.

The corresponding values of the elements of the degree of truth function vector of the transitions that satisfy the excitation condition in the $C_f$type FPN are:

$$f = (0.370; 0.300; 0.900; 0.400; 0.300; 0.450; 0.500; 0.900; 0.200).$$

The corresponding values of the elements of the excitation threshold vector for the execution of the enabled transitions in the $C_f$type FPN are:

$$\lambda = (0.100; 0.150; 0.250; 0.300; 0.350; 0.400; 0.450; 0.500; 0.600).$$

The values of the elements of the initial marking vector of in the $C_f$type FPN are:

$$\mu_0 = (0.130; 0.250; 0.350; 0.450; 0.500; 0.550; 0.600; 0.650; 0.700; 0.750; 0.800)$$

The graph diagram of the control model of the cassette conveyor movement is shown in Figure 7.

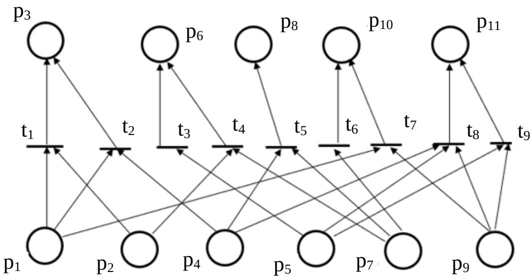

Figure 7. Graph diagram of the control model of the cassette conveyor movement in mechanical processing production

The fourth chapter is dedicated to the issue of developing software for fuzzy inference in the control of parallel operating processes.

The development of software for modeling parallel operating processes using the extensions of Petri nets.

An algorithm and software have been developed for modeling parallel processes using the extensions of Petri nets. The developed application software system consists of the following main program modules: Network text description module, network graphic description module, network property analysis modules, simulation module.

Algorithm of operation of software modules for modeling parallel processes using Petri net expansions

Module 1. Creation of matrices for the input and output incidence and distribution function membership degrees of the transition set, initial marking, and the membership degree matrices of the initial marking's distribution function.

The beginning of the algorithm.

Step 1.1 Formation of the structural elements of the Petri net. $g^{-}_{j,i}, g^{+}_{i,j}, w^{-}_{j,i},\ i=\overline{1,r}\quad j=\overline{1,m+n}$

Step 1.2. Formation of the initial marking and the elements of the unit vector. $\mu_j, E_j,\ j=\overline{1,m+n}$

Module 2. Finding the enabled transition.

Step 2.1 $i=1$ accepted;

Step 2.2 if $i>r$ the condition is met, a deadlock state is declared; otherwise, proceed to *Step 2.3*.

Step 2.3 if $i > r$ the condition is not met, then for $j = \overline{1, m}$ If $g_{ji}^{-} \neq \varepsilon$ is met, $n1 = card(g_{ji}^{-})$, $p = copy(\mu_j, 1, n1)$ it is determined; otherwise, proceed to Step 2.2.

Step 2.4 if $p \neq g_{ji}^{-}$ the condition is met, then $i = i + 1$ is accepted; otherwise, proceed to *Step 2.2*;

Step 2.5 for $j = \overline{m+1, m+n}$ calculated.

Step 2.6 if $g_{ji}^{-} \neq \varepsilon$ the condition is met, then $\tilde{\mu}_j = \varepsilon$, $n1 = card(\mu_j)$ calculated, Otherwise, proceed to *Step 2.2*;

Step 2.7 $k = n1{,}1$ is calculated within the value range for: $\tilde{\mu}_j = \tilde{\mu}_j copy(\mu_j, k, 1)$.

Step 2.8 $n1 = card(g_{ji}^{-})$ calculated;

Step 2.9 $p = copy(\mu_j, 1, n1)$ calculated;

Step 2.10 if $p \neq g_{ji}^{-}$ the condition is met, then $i = i + 1$ is accepted; otherwise, proceed to *Step 2.2*;

Step 2.11 for $j = \overline{m+1, m+n}$ is calculated within the value range for. İf $g_{ji}^{-} \neq \varepsilon$ the condition is met, then $\tilde{\mu}_j = \varepsilon$ accepted, $n1 = card(\mu_j)$ calculated, otherwise, proceed to *Step 2.12***;**

Step 2.12 $k = n1{,}1$ is calculated within the value range.$\tilde{\mu}_j = \tilde{\mu}_j copy(\mu_j, k, 1)$

Step 2.13 $n1 = card(g_{ji}^{-})$ accepted;

Step 2.14 $p = copy(\mu_j, 1, n1)$ calculated;

Step 2.15 if $p \neq g_{ji}^{-}$ the condition is met, $i = i + 1$ accepted, otherwise, proceed to *Step 2.2***;**

Module 3. The distribution function vector of the new marking:

Step 3.1. is checked for $j = \overline{1, m+n}$;

Step 3.2. $m1 = card(\mu_j)$

Step 3.3. $n1 = card(g_{ji}^{-})$

Step 3.4. if $j \leq m$ the condition is met, then $\mu_j = copy\left(\mu_j, n1 + 1, m1 - n1\right) * g_{ij}^{+}$ calculated, otherwise, $\mu_j = copy\left(\mu_j, 1, m1 - n1\right) * g_{ij}^{+}$ calculated;

Module 4. Calculation of the elements of the input membership function matrix of the transition set.

Step 4.1 for $k = 1, m + n$ condition is checked $min = w_{ij}^{-}$;

Step 4.2 if $W_{ij}^{-} <$ min the condition is met, then $min = W_{ji}^{-}$ accepted, otherwise, proceed to *Step 4.1;*

Step 4.3 for $j = \overline{2, m + n}$, $W_{ik}^{+} = min$ the condition is met, otherwise, proceed to *Step 4.1;*

Module 5. Calculation of the elements of the output membership function matrix of the transition set:

Step 5.1 for $k = 1, m + n$ in the range of $z = 1$ accepted;

Step 5.2 $j = 1, m + n$ calculated in the range :

Step 5.3 if $W_{ji}^{-} \neq 0$, then it is calculated $z = z \cdot W_{ji}^{-}$ otherwise, proceed to *Step 5.2*;

Step 5.4 $W_{ik}^{+} = z$ *is* accepted;

Module 6. Creation of the membership function matrix for the new marking:

Step 6.1 for $j = \overline{1, m + n}$ condition is checked :

Step 6.2 if $\mu_j = 0$ the condition is met, $E_j = 0$ accepted, otherwise , $\ell = card(\mu_j)$, $E_j = [W_{jk}^{+}]^{\ell}$ is calculated.

End of the algorithm.

Implementation of fuzzy inference in the control of parallel-operating devices in the MATLAB environment

The MATLAB system is a comprehensive software suite for numerical calculations, computer modeling, and performing computational experiments, integrating both classical and modern mathematics, as well as engineering tasks. MATLAB is an excellent system consisting of the base program and various extension packages. All of this facilitates the flexible realization of necessary problem-solving by using hundreds of built-in functions that include various mathematical procedures and computational algorithms in the working environment.

By selecting the **'Membership Functions'** command in the **Edit** menu, trapezoidal membership functions have been defined for the linguistic variables 'Load coefficient of the input accumulator of the processing unit,' 'Movement speed of the cassette conveyor' (input), and 'Valve of the pneumatic motor of the cassette conveyor' (output). By entering the appropriate ranges in the Range and Display Range fields, we define the domain (fuzzy set) of the input and output linguistic variables. The description of the trapezoidal membership function for the fuzzy values of the linguistic variable 'Load coefficient of the input accumulator of the processing unit' is shown in the figure.

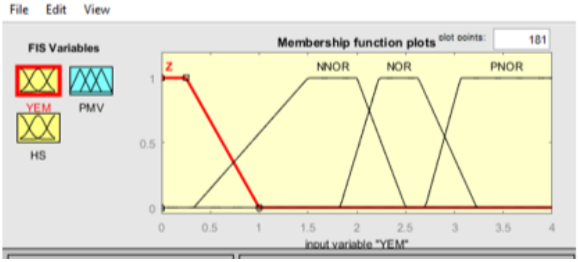

Figure 8. Description of TMF for the fuzzy set of the linguistic variable 'Load coefficient of the input accumulator of the processing unit

We define the domain of the linguistic variables in the range [0,4]: $\widetilde{L1}_1$ = [0, 0, 0.25, 1] Z-zero; $\widetilde{L1}_2$= [0.33, 1.5, 2, 2.5] NNOR-negative normal; $\widetilde{L1}_3$ = [1.8, 2.22, 2.63, 3.23] NOR-normal; $\widetilde{L1}_4$= [2.7, 3.06, 4, 4] PNOR-positive normal (fiq. 8).

The linguistic variable 'Movement speed of the cassette conveyor' is defined in the range [0,20] as TL2 = (minimum, average, maximum) set of terms. $\widetilde{L2}_1$ = [0, 1.56, 3.15, 7.91] MİN-minimum; $\widetilde{L2}_2$= [2.88, 8.78, 11.9, 16.8] MİD-middle; $\widetilde{L2}_3$ = [11.5, 15.1, 17.4, 20.1] MAX-maximum. (fig 9).

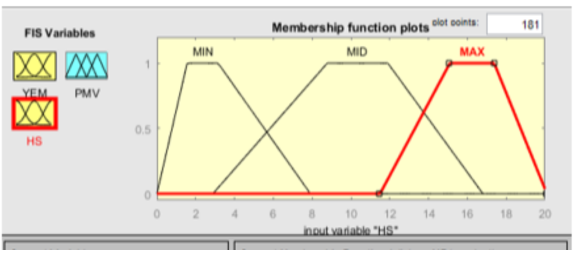

Figure 9. Description of TMF for the fuzzy set of the linguistic variable 'Movement speed of the cassette conveyor

The fuzzy set of terms for the linguistic variable 'Valve of the pneumatic motor of the cassette conveyor' (output) has also been defined in the range [0,90] using the trapezoidal membership function in the same manner. TL3=(small right angle, large right angle, stable state, small left angle, large left angle). $\widetilde{L3}_1$ = [9.286 19.29 29.29 39.29] LS-left small ; $\widetilde{L3}_2$= [0 0 10 23.21] LB- left big; $\widetilde{L3}_3$ =[27.97,37,43,55] SS-stable state; $\widetilde{L3}_4$= [44,55.65,75] RS- right small; $\widetilde{L3}_5$ =[65,75,90,90] RB-right big) (fig10).

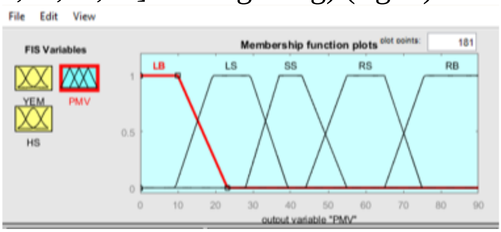

Figure 10. Description of TMF for the fuzzy set of terms of the linguistic variable 'Valve of the pneumatic motor of the cassette conveyor (output)

Rule Editor is used, and fuzzy production rules are developed.

After the fuzzy production rules are developed, the results of the logical inference system are obtained. For this, the Rules command in the View menu is selected. By entering the corresponding values of the input variables in the Input field of the opened window, the values of the output variables and the result diagram are obtained. The three-dimensional surface representation of the fuzzy (FS) logical inference system was obtained using the Surface command in the View menu. (fig 11).

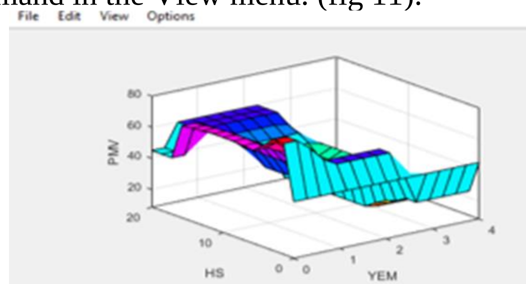

Figure 11. Three-dimensional representation of the defuzzification result for the output variable "Valve of the pneumatic motor of the cassette conveyor"

The rule base of the FS inference system is based on an empirical knowledge base or expert knowledge across various problem domains.

A fuzzy logic inference system has been developed in MATLAB using the FIS graphical editor included in the FLT package for the decision-making model of cassette conveyor control in the form of a C_f type FS.

THE MAIN RESULTS OF THE DISSERTATION WORK

1. By generalizing the results of the analysis of literature sources and practical experience regarding the modeling, investigation, and control of dynamic discrete processes operating under the principle of parallelism and complex characteristics using PN extensions, the aim of the dissertation work has been formulated. Additionally, the issues requiring resolution to achieve this aim have been identified.
2. A control model based on an extension of PN has been developed for an automated system consisting of parallel modules operating along a single route.
3. In the mechanical processing production process, control models using a FPN have been developed for processing centers operating based on the principle of parallelism with two and three flexible production modules. The results are described using graph-schemes of PN.
4. Based on the linguistic variables of input (load coefficient of the processing unit's input accumulator and movement speed of the cassette conveyor) and output (displacement angles of the pneumatic motor of the cassette conveyor), fuzzy production rules for the control of the cassette conveyor have been developed. Using the FLT package, fuzzification of input and output linguistic variables has been implemented in the MATLAB environment, and the output linguistic variable's quantitative values have been obtained using the center of gravity method with the application of the Mamdani algorithm.

5. The control model of the cassette conveyor in the mechanical processing production system has been described in the form of a C_f type fuzzy Petri net (FPN). The positions and transitions included in its structure have been described according to the rule base based on fuzzy production systems, and the control model of the cassette conveyor's movement has been developed in the form of a graph-scheme based on the structure of the C_f type FPN.

6. The description of parallel operating processes using FPN has been analyzed, and the implementation of modeling discrete objects with modifications of the FPN has been developed. The specification and verification of software for the realization of the control models and algorithms have been substantiated, and the appropriateness of using these models has been confirmed. Fuzzy inference for controlling parallel-operating devices has been implemented using the FLT extension package in the MATLAB environment.

THE MAIN RESULTS OF THE DISSERTATION ARE REFLECTED IN THE FOLLOWING PUBLISHED SCIENTIFIC ARTICLES:

1. Ahmadov M.A., Zeynalabdiyeva I.S. Operational model of parallel dynamic objects in the form of a fuzzy Petri net," in Applied Mathematics and New Information Technologies, III National Scientific Conference, -Sumgait, -2016, -pp. 263-264.

2. Mustafayev V.A., Zeynalabdiyeva I.S., Rufullayeva R.A."Control model of an automated complex consisting of parallel modules, Scientific News of Sumgayit State University. Natural and Technical Sciences Section, Sumgayit: Sumgayit State University, 2017, Vol. 17, No. 4, pp. 61-65.

https://www.sdu.edu.az/userfiles/file/scientific_publications/EX%204-17_T.pdf

3. Zeynalabdiyeva I.S., Rufullayeva R.A., Control model of an automated complex consisting of parallel modules, *Current Scientific and Practical Problems of Software Engineering,* I National

Conference, Baku: Institute of Information Technologies, May 17, 2017, pp. 70-71.

4. Zeynalabdiyeva I.S. Structure of the control model of parallel-operating modules," *XXI National Scientific Conference of Doctoral Students and Young Researchers*, Baku: Baku State University, 2017, pp. 56-58.

5. Ataev G.N., Zeynalabdiyeva I.S., "Control model of parallel-operating production modules in the mechanical processing system," *Mathematical Methods in Engineering and Technologies (MMET)*, Saratov State Technical University, Saratov, Russia, 2017, pp. 111-116.

https://www.elibrary.ru/item.asp?id=41153772

6. Ataev G.N., Zeynalabdiyeva I.S., "Production model of the control of the mechanical processing production module," *International Scientific Conference, Science, Technology, Production*, Ufa State Technical University in Salavat, 2017, pp. 275-276.

7. Ataev G.N., Zeynalabdiyeva I.S., "Production rules for the control of parallel-operating flexible production modules in the mechanical processing system," *Information Systems and Technologies: Achievements and Perspectives, International Scientific Conference*, Sumgayit, 2018, pp. 252-256.

8. Ataev G.N., Mustafayev V.A., Zeynalabdiyeva I.S., "Fuzzy control model of parallel-operating flexible production modules in the mechanical processing system," *Instrument Engineering and Automated Electric Drive in the Fuel-Energy Complex and Housing and Utilities Sector. Proceedings of the IV National Scientific and Practical Conference*, Kazan State Energy University, Kazan, Russia, 2018, pp. 3-10.

9. Zeynalabdiyeva I.S., "Fuzzy control model of parallel-operating flexible production modules in the mechanical processing system," *XXII National Scientific Conference of Doctoral Students and Young Researchers*, Baku: APU, 2018, pp. 235-238.

10. Ahmadov M.A., Zeynalabdiyeva I.S., "Analysis of the current state of research on the modeling methods of parallel-operating production modules," *Scientific News of Sumgayit State University.*

Natural and Technical Sciences Section, Sumgayit: Sumgayit State University, 2019, Vol. 19, No. 2, pp. 66-71.

11. Zeynalabdiyeva I.S. "Production rules determining the triggering of transitions and state changes in fuzzy models," *XXIII National Scientific Conference of Doctoral Students and Young Researchers*, Baku: AUAC,- 2019,- pp. 229-231.

12. Mustafayev V.A., Zeynalabdiyeva I.S., "Control model of production modules in the form of fuzzy Petri nets," *Information Systems and Technologies, Achievements and Perspectives, II International Scientific Conference*, Sumgayit, 2020, pp. 262-264.

13. Atayev G.N., Zeynalabdiyeva I.S. Decision-making model for the control of parallel-functioning processing devices. // The 8th International Conference on Control and Optimization with Industrial Applications (COIA 2022), − Baku: −27-28 August,−2020,-p.99-101. http://coia-conf.org/en/view/pages/22

14. Ahmadov M.A., Zeynalabdiyeva I.S., "Production model of cassette conveyor movement in mechanical processing production," *Applied Mathematics and New Information Technologies, IV National Scientific Conference*, Sumgayit, 2021, pp. 120-123.

15. Mustafayev V.A., Zeynalabdıyeva İ.S., O.Ja. Kravets Control model of parallel functioning production modules as fuzzy petri nets // Journal of Physics: Conference Series. Published under licence by IOP Publishing Ltd Volume 2094 022003 - 2021 https://iopscience.iop.org/article/10.1088/1742-6596/2094/2/022003/pdf doi:10.1088/1742-6596/2094/2/022003

16. Zeynalabdıyeva İ.S. Fuzzy output control of the movement of the cassette conveyor in the production of mechanical processing // − Sumgayit: Sumgayit State University, Scientific News, Natural and Technical Sciences Section, Vol. 21, No. 3, 2021, pp. 79-85.https://elibrary.ru/item.asp?id=47176427

17. Ataev G.N., Zeynalabdiyeva I.S., "Decision-making model for the control of parallel-operating processing devices," Sumgayit State University, Scientific News, Natural and Technical Sciences Section, Vol. 22, No. 2, 2022, pp. 64-69.

18. Zeynalabdiyeva I.S., "Decision-making model for the control of cassette conveyor movement in mechanical processing

production," Bulletin of the Ufa State Aviation Technical University, Republic of Bashkortostan, Ufa, Russia, Vol. 26, No. 2, 2022, pp. 126-133.

19. Zeynalabdiyeva I.S., "Production Model of Cassette Conveyor Motion Control in Mechanical Processing," *IECHCI2022, International East Conference on Human-Computer Interaction*, Nakhchivan, Azerbaijan, 2022, pp. 138-140.

Author's individual participation in the published works:

[1] Describing the structure and operation of parallel-character objects within fuzzy conditions in the form of fuzzy Petri nets;

[2], [3] Building a network model for an automated complex along a route;

[5], [12] Developing a fuzzy control model for parallel-operating production modules in a mechanical processing system;

[6], [17] Developing a decision-making model with production rules for controlling two parallel-operating flexible manufacturing modules (FMM);

[7] Developing production rules for control in a mechanical processing system with three FMMs operating in parallel;

[8] Developing a fuzzy control algorithm for parallel-operating production modules in a mechanical processing system;

[10] Analyzing the current state of research on modeling methods for parallel-operating production modules;

[13], [15] Developing a rule base for controlling the movement of a cassette conveyor in mechanical processing production;

[14] Developing a fuzzy logic inference mechanism.

The defense will be held on 8 April 2025 at 14^{00} at the meeting of the Dissertation Council ED 2.48 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan State Oil and Industry University.

Address: AZ1010, Baku city, Azadlig avenue 16/21
e-mail: info@asoiu.edu.az

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