Automated evaluation models and algorithms for optimizing exercise assessments in food production training complexes

Ivan Polevshchikov[1,2,3*], and *Elena* Litvinova[1]

[1]Russian Biotechnological University, Moscow, Russia
[2]K.G. Razumovsky Moscow State University of Technologies and Management (the First Cossack University), Moscow, Russia
[3]Perm National Research Polytechnic University, Perm, Russia

Abstract. The article is devoted to the development of models and algorithms of intelligent training complexes for training engineering specialists in the food industry. A method has been developed for comprehensive assessment of the quality of performing exercises on optimization problems in virtual environment. The method differs from the known ones in many parameters that determine the structure and specificity of these problems. It is formalized based on of fuzzy sets that describe incomplete knowledge when comparing the mathematical model of the problem created by the student with the reference one. The use of intelligent training complexes, in the software of which the presented method is implemented, will allow for ongoing monitoring and self-monitoring of students' knowledge and skills when studying disciplines in the field of developing software for automated control systems for production processes. The use of intelligent training complexes ensures the collection and analysis of data on the dynamics in the formation of professional knowledge and skills among students in the development of mathematical software for automated control systems. Accordingly, the time for conducting control activities for the teacher is reduced, and the accuracy of the results of monitoring the formation of knowledge and skills among students is increased.

1 Introduction

Improving the quality of training of engineering specialists in the food industry (in particular, food production technologists, specialists in automation, informatization, robotization of production processes) is an important task of modern technological universities. This problem is especially important in connection with current trends in import substitution, ensuring food security, and the widespread introduction of intelligent automated control systems (ACS) for technological processes and production in the food sector [1].

For effective training of specialists in various sectors of the economy, including in the food industry, Russian and foreign authors presented research and development in the field

* Corresponding author: i.s.polevshchikov@mail.ru

of computer simulators for personnel training [2, 3] and other similar automated control systems for the educational process [4-7]. One of the most important functions of such systems - monitoring knowledge and skills during the learning process - in practice often comes down to either knowledge testing [8], which has shortcomings, or to time-consuming "manual" checking by the teacher of the results of assignments. Creating a computer simulator for training specialists in a certain subject area includes the development of models and algorithms for simulating a given subject area when performing exercises on the simulator and assessing knowledge and skills based on the results of the exercises.

The relevance of this research lies in the development of models and algorithms of intelligent training complexes for training engineering specialists (in particular, in the food industry) in the tasks of optimizing production processes as the basis for mathematical support of modern automated control systems for production processes. A method has been developed for comprehensive assessment of the quality of performing exercises on optimization problems in the virtual environment of intelligent training complexes, which differs from the known ones in many parameters that determine the structure and specificity of these tasks, and is also formalized, based on fuzzy sets that describe incomplete knowledge when comparing the mathematical model of the problem created by the student , with the reference one. The features of the developed assessment method are presented below.

2 Algorithms for evaluating graphical models of optimization problems

The works [1, 9, 10] described the concept, models and algorithms of an intelligent training complex for training engineering specialists (in particular, students in areas of training in the field of automation, information, robotization). Specific features of this intelligent training complex, which help to increase the level of formation of knowledge and skills among specialists and reduce the labor intensity of organizing the educational process, are: setting up exercises by the teacher, automatic generation of individual exercise options for each student, automatic evaluation of the results of the exercises. In particular, such exercises are practical tasks to develop initial skills in developing and analyzing mathematical models of typical optimization problems.

Next, we describe the developed method for comprehensive assessment of the quality of performing exercises on optimization problems in a virtual environment of the training subsystem as a key component of intelligent training complexes.

Various algorithms for calculating estimates for completing exercises in the development and analysis of mathematical models of optimization problems are acceptable considering the degree of correct solution of the exercise depending on the specifics of the problem.

Fig. 1 shows in the form of an Activity UML diagram an algorithm for evaluating the implementation of intelligent training complexes for constructing a mathematical model of an object or process within the framework of an optimization problem.

The estimation algorithm in Fig. 1 is based on automatic analysis of the correspondence of the structure of the mathematical model $M_{\text{tr.}}$ correct (reference) solution to the exercise and structure of the mathematical model $M_{\text{st.}}$ solutions proposed by the student, which may include errors. Models $M_{\text{tr.}}$ and $M_{\text{st.}}$ describe in set-theoretic form the structure and properties of the studied model of the optimization problem. The reference solution to the exercise is generated automatically by training and education subsystem based on the problem statement.

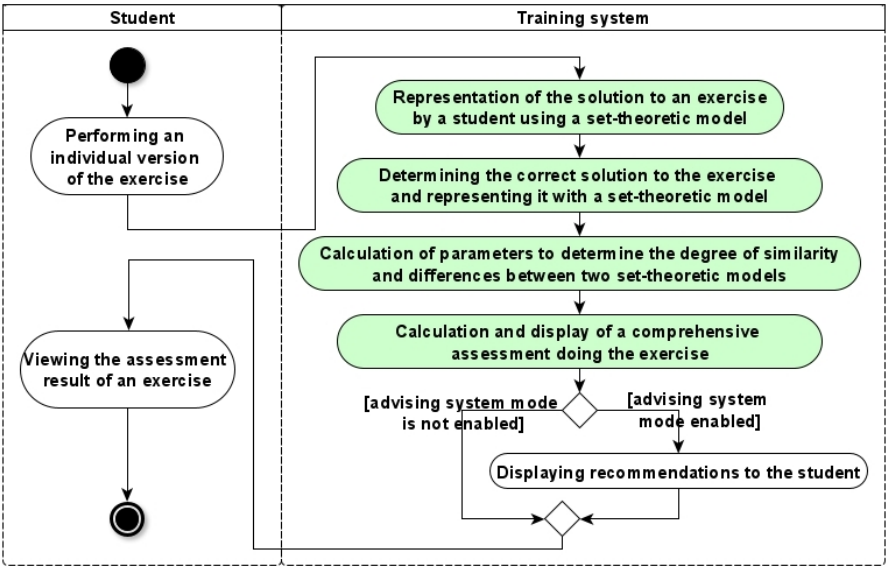

Fig. 1. Algorithm for assessing exercise performance of intelligent training complexes in training and education subsystem.

Standard training and education subsystem algorithms have been developed for evaluating exercises for developing graphical models of the optimization problems under consideration. Let's consider these algorithms using the example of a graph construction exercise based on the mathematical formulation of a Boolean linear programming problem to determine the min/max path.

Figure 2 shows the correct (reference) graph, which the student must construct based on the mathematical formulation of the problem. Figure 3 shows a graph constructed by a student with errors.

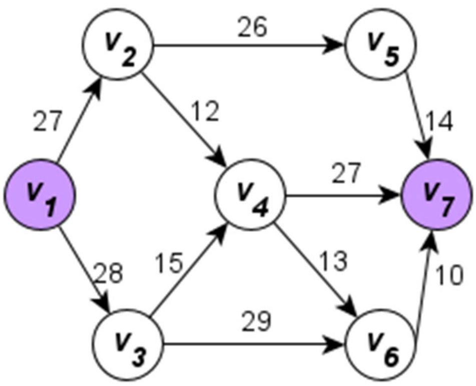

Fig. 2. Correct (reference) graph.

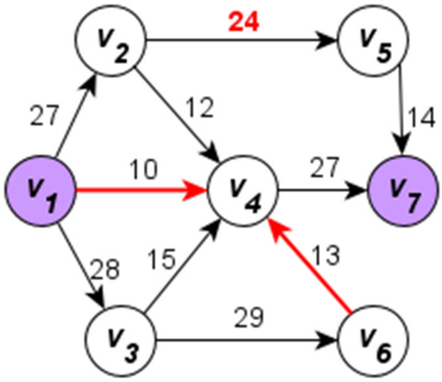

Fig. 3. Graph constructed by a student (with errors).

A simplified estimation algorithm is based on determining the complete coincidence of graph arcs and their weights. The steps of this algorithm using the example of comparing graphs from Fig. 2 and fig. 3:

1. The result of correct execution of the exercise is determined:

$$M_{\text{tr.}} = \{\langle v_1, v_2, 27\rangle, \langle v_1, v_3, 28\rangle, \langle v_2, v_4, 12\rangle, \langle v_2, v_5, 26\rangle, \langle v_3, v_4, 15\rangle, \langle v_3, v_6, 29\rangle, \langle v_4, v_6, 13\rangle, \langle v_4, v_7, 27\rangle, \langle v_5, v_7, 14\rangle, \langle v_6, v_7, 10\rangle\}.$$

2. The result of the student performing the exercise is determined:

$$M_{\text{st.}} = \{\langle v_1, v_2, 27\rangle, \langle v_1, v_3, 28\rangle, \langle v_1, v_4, 10\rangle, \langle v_2, v_4, 12\rangle, \langle v_2, v_5, 24\rangle, \langle v_3, v_4, 15\rangle, \langle v_3, v_6, 29\rangle, \langle v_4, v_7, 27\rangle, \langle v_5, v_7, 14\rangle, \langle v_6, v_4, 13\rangle\}.$$

3. Parameters that influence the assessment value are calculated:

$$N_{\text{tr.}} = |M_{\text{tr.}}| = 10;\ \text{N}_{\text{con.}} = |\text{M}_{\text{tr.}} \cap \text{M}_{\text{st.}}| = 7;\ \text{N}_{\text{def.}} = |\text{M}_{\text{st.}}| \text{-} \text{N}_{\text{con.}} = 3.$$

4. The score for completing the exercise $K \in [0;1]$ is calculated:

$\text{K} = \frac{\text{N}_{\text{con.}}}{\text{N}_{\text{tr.}} + \text{N}_{\text{def.}}} = \frac{7}{10+3} \approx 0{,}54$ (i.e. the student constructed the graph approximately 54% correctly).

The improved estimation algorithm is based on taking into account the partial coincidence of arcs using fuzzy sets, which make it possible to model uncertainty when comparing two graphs:

1. The sets $M_{\text{tr.}}$ and $M_{\text{st.}}$ are transformed into fuzzy sets $M_{\text{tr.}}$ and $M_{\text{st.}}$. The values of the membership function for all elements of fuzzy set carriers will be equal to 1:

$$M_{\text{tr.}} = \{(\langle v_1, v_2, 27\rangle, 1), (\langle v_1, v_3, 28\rangle, 1), (\langle v_2, v_4, 12\rangle, 1), (\langle v_2, v_5, 26\rangle, 1), (\langle v_3, v_4, 15\rangle, 1), (\langle v_3, v_6, 29\rangle, 1), (\langle v_4, v_6, 13\rangle, 1), (\langle v_4, v_7, 27\rangle, 1), (\langle v_5, v_7, 14\rangle, 1), (\langle v_6, v_7, 10\rangle, 1)\};$$

$$M_{\text{st.}} = \{(\langle v_1, v_2, 27\rangle, 1), (\langle v_1, v_3, 28\rangle, 1), (\langle v_1, v_4, 10\rangle, 1), (\langle v_2, v_4, 12\rangle, 1), (\langle v_2, v_5, 24\rangle, 1), (\langle v_3, v_4, 15\rangle, 1), (\langle v_3, v_6, 29\rangle, 1), (\langle v_4, v_7, 27\rangle, 1), (\langle v_5, v_7, 14\rangle, 1), (\langle v_6, v_4, 13\rangle, 1)\}.$$

2. A fuzzy relation Q is defined, showing the correspondence between the possible types of arcs of these graphs depending on whether the direction and weight in them coincide: $\mu_{ij} = 1$– if the initial and final vertices, direction and weight of the arc coincide; $\mu_{ij} = 0.5$ – when either only the direction or only the weight of the arc coincides; $\mu_{ij} = 0.25$ – when the direction and weight of the arc do not coincide; $\mu_{ij} = 0$ – if the start or end vertex does not match.

3. Based on the relationship Q, fuzzy sets $M_{\text{tr.}}$ and $M_{\text{st.}}$ are defined that determine the degree of correspondence between the graphs:

$$M'_{\text{tr.}} = \{(\langle v_1, v_2, 27\rangle, 1), (\langle v_1, v_3, 28\rangle, 1), (\langle v_2, v_4, 12\rangle, 1), (\langle v_2, v_5, 24\rangle, 0.5), (\langle v_3, v_4, 15\rangle, 1), (\langle v_3, v_6, 29\rangle, 1), (\langle v_4, v_7, 27\rangle, 1), (\langle v_5, v_7, 14\rangle, 1), (\langle v_6, v_4, 13\rangle, 0.5)\};$$

$M'_{\text{st.}} = \{(\langle v_1, v_2, 27\rangle, 1), (\langle v_1, v_3, 28\rangle, 1), (\langle v_2, v_4, 12\rangle, 1), (\langle v_2, v_5, 26\rangle, 0.5),$
$(\langle v_3, v_4, 15\rangle, 1), (\langle v_3, v_6, 29\rangle, 1), (\langle v_4, v_6, 13\rangle, 0.5), (\langle v_4, v_7, 27\rangle, 1), (\langle v_5, v_7, 14\rangle, 1)\}.$

4.

The parameters are calculated to calculate the assessment of the exercise (in the formulas below *z* it means the arc of the graph)

$N'_{\text{tr.}} = |M_{\text{tr.}}| = 10;$

$M_{\text{con.}} = M_{\text{tr.}} \cap M'_{\text{st.}} =$
$\{(\langle v_1, v_2, 27\rangle, 1), (\langle v_1, v_3, 28\rangle, 1), (\langle v_2, v_4, 12\rangle, 1), (\langle v_2, v_5, 26\rangle, 0.5),$
$(\langle v_3, v_4, 15\rangle, 1), (\langle v_3, v_6, 29\rangle, 1), (\langle v_4, v_6, 13\rangle, 0.5), (\langle v_4, v_7, 27\rangle, 1), (\langle v_5, v_7, 14\rangle, 1)\};$

$N'_{\text{con.}} = \sum \mu_{M_{\text{con.}}}(z) = 8;$

$M_{\text{def.}} = M_{\text{st.}} \backslash M'_{\text{tr.}} = \{(\langle v_1, v_4, 10\rangle, 1), (\langle v_2, v_5, 24\rangle, 0.5), (\langle v_6, v_4, 13\rangle, 0.5)\};$

$N'_{\text{def.}} = \sum \mu_{M_{\text{def.}}}(z) = 2.$

5. The exercise performance score is calculated $K' \in [0; 1]$:

$K' = \frac{N'_{\text{con.}}}{N'_{\text{tr.}} + N'_{\text{def.}}} = \frac{8}{10+2} \approx 0.67$ (i.e. the student constructed the graph approximately 67% correctly).

The grade $K' \approx 0.67$, obtained using an improved algorithm, higher than the estimate $K \approx 0{,}54$, obtained using a simpler algorithm, since partially correctly constructed arcs are taken into account. The improved algorithm allows you to more accurately evaluate the execution of the exercise when the graph constructed by the student partially corresponds to the correct graph, which helps to increase the efficiency of collecting and processing data on how specialists study the fundamentals of developing and analyzing models for various optimization problems.

When calculating the *K* value, it is possible to take into account additional factors that influence the assessment of the exercise. For example, when there is limited time to solve a problem, the value of *K* may be adjusted if the student was unable to meet the time limit. The accuracy of the *K* estimate is facilitated by taking into account the specifics of the optimization problem (for example, the presence of unique starting and ending vertices in the graph).

3 Algorithms for estimating models of mathematical programming problems

In some exercises, the mathematical model that needs to be built includes several components that are assessed separately in accordance with a certain algorithm, and then, based on the assessments of individual components of the model, the final assessment of the exercise is determined. An algorithm for evaluating an exercise for constructing a model of a mathematical programming problem is presented using the example of comparing the reference (based on Fig. 2) and the mathematical models of the Boolean linear programming problem built by the student (with errors) (Table 1). An algorithm for estimating a simplified version of the exercise with a known number of variables in the objective function, the number of constraints, and the number of variables in the constraints:

Table 1. Mathematical models of the Boolean linear programming problem for comparison.

Reference (correct) model	**Model built by a student with errors (incorrect elements of the model are highlighted)**
$27x_{12}+28x_{13}+12x_{24}+26x_{25}+15x_{34}+29x_{36}+$ $+13x_{46}+27x_{47}+14x_{57}+10x_{67} \to \max$	$27x_{12}+28x_{13}+12x_{24}+26x_{25}+15x_{34}+29x_{36}+$ $+13x_{46} \underline{-27}x_{47} \underline{-14}x_{57} \underline{-10}x_{67} \to \max$

$x_{12}+x_{13}=1$ $x_{47}+x_{57}+x_{67}=1$ $x_{12}-x_{24}-x_{25}=0$ $x_{13}-x_{34}-x_{36}=0$ $x_{24}+x_{34}-x_{46}-x_{47}=0$	$x_{25}-x_{57}=0$ $x_{36}+x_{46}-x_{67}=0$ $x_{12}, x_{13}, x_{24}, x_{25}, x_{34}, x_{36}, x_{46}, x_{47}, x_{57}, x_{67} \in \{0,1\}$	$x_{12}+x_{13}=1$ $x_{47}+x_{57}\underline{-x_{67}=0}$ $x_{12}-x_{24}-x_{25}\underline{\geq 0}$ $x_{13}-x_{34}-x_{36}=0$ $x_{24}\underline{-x_{34}+x_{46}}-x_{47}=0$	$x_{25}\underline{+x_{57}}=0$ $x_{36}+x_{46}\underline{+x_{67}}=0$ $x_{12}, x_{13}, x_{24}, x_{25}, x_{34}, x_{36}, x_{46}, x_{47}, x_{57}, x_{67} \in \{0,1\}$

1. Calculation of the assessment of the correctness of the objective function definition $K_{\text{of.}} \in [0;1]$ according to the equation $K_{\text{of.}} = \frac{\sum_i^{N_{\text{of.}}} w_i^{\text{of.}} k_i^{\text{of.}}}{\sum_i^{N_{\text{of.}}} w_i^{\text{of.}}}$, where $k_i^{\text{of.}} \in [0;1]$ – assessment of i-th component of the objective function, determined by the student (sign of the variable, right side), $w_i^{\text{of.}}$ – weight coefficient of i-th component of objective function (reflecting its importance and/or difficulty in the exercise).

In the equation $K_{\text{of.}} = \frac{2\cdot 8}{2\cdot 11} \approx 0.73$ there are totally 11 components of the objective function: choice of signs of 10 variables ("plus" or "minus") ($w_i^{\text{of.}} = 2$); choice of min/max objective function ($w_i^{\text{of.}} = 2$). The student chose correctly 7 out of 10 characters and max objective function.

2. Calculation of the assessment of the correctness of the definition of each j-th constraint ($j = \overline{1, N_{\text{res.}}}$, where $N_{\text{res.}}$ – total number of restrictions) $K_j^{\text{res.}} \in [0;1]$ according to the equation $K_j^{\text{res.}} = \frac{\sum_q^{N_j^{\text{res.}}} w_{jq}^{\text{res.}} k_{jq}^{\text{res.}}}{\sum_q^{N_j^{\text{res.}}} w_{jq}^{\text{res.}}}$, where $k_{jq}^{\text{res.}} \in [0;1]$ – assessment of q-th component of j -th restrictions determined by the learner (sign of the variable, relation, right side), $w_{jq}^{\text{res.}}$ – weight coefficient of q-th component of the j-th constraint (defined similarly $w_i^{\text{of.}}$).

In the equation $K_1^{\text{res.}} = \frac{2\cdot 3+3\cdot 1}{2\cdot 3+3\cdot 1} = 1$ there are 4 components of restrictions $j = 1$, which the student chose completely correctly: choice of signs of 2 variables ("plus" or "minus") ($w_{jq}^{\text{res.}} = 2$); selection of restriction sign (=,≥,≤) ($w_{jq}^{\text{res.}} = 3$); selecting the right side of the constraint (0 or 1) ($w_{jq}^{\text{res.}} = 2$). Other values: $K_2^{\text{res.}} \approx 0.64$, $K_3^{\text{res.}} \approx 0.73$, $K_4^{\text{res.}} = 1$, $K_5^{\text{res.}} \approx 0.69$, $K_6^{\text{res.}} = 0.875$, $K_7^{\text{res.}} \approx 0.82$.

3. Calculating an estimate of the correctness of the definition of a variable constraint $K_{\text{var.}} \in [0;1]$. In the equation $K_{\text{var.}} = 1$ (variable type is correctly defined as boolean).

4. Calculation of the final assessment of the correctness of the definition of the mathematical model of the Boolean linear programming problem $K \in [0;1]$ based on equation $K = \frac{w_{\text{of.}} K_{\text{of.}} + \sum_j^{N_{\text{res.}}} w_j^{\text{res.}} K_j^{\text{res.}} + w_{\text{var.}} K_{\text{var.}}}{w_{\text{of.}} + \sum_j^{N_{\text{res.}}} w_j^{\text{res.}} + w_{\text{var.}}}$, where $w_{\text{of.}}$, $w_j^{\text{res.}}$, $w_{\text{var.}}$ – weighting coefficients of estimates of the components of the model of the Boolean linear programming problem, calculated in steps No. 1-3. Here $w_{\text{var.}} = 3$, because one needs to choose from 3 values: ≥0; ≥0 whole numbers; {0,1}. In the equation: $K \approx 0.82$.

A more advanced version of this exercise requires you to determine the number of variables in the objective function and in each constraint. An algorithm is used to compare the model component built by the learner and the reference component. For example, in the mathematical model of the Boolean linear programming problem about the maximum path in a graph, the reference (correct) constraint for node No. 4 of the graph is:

$$x_{24} + x_{34} - x_{46} - x_{47} = 0$$

Constraint for node No. 4 of the graph, constructed by a student with errors:

$$x_{24} + x_{34} \underline{\pm} x_{46} - x_{47} \underline{\mathbf{-x_{57}}} = 0$$

The evaluation algorithm is based on determining the complete coincidence of the elements of the left sides of the constraints:

1. The result of correct execution of the task is determined:

$$M_{\text{tr.}} = \{+x_{24}, +x_{34}, -x_{46}, -x_{47}\}.$$

2. The result of the student completing the task is determined:

$$M_{\text{st.}} = \{+x_{24}, +x_{34}, +x_{46}, -x_{47}, -x_{57}\}.$$

3. Parameters that influence the value of the estimate are calculated:

$$N_{\text{tr.}} = |M_{\text{tr.}}| = 4;\ \text{N}_{\text{con.}} = |\text{M}_{\text{tr.}} \cap \text{M}_{\text{st.}}| = 3;\ \text{N}_{\text{def.}} = |\text{M}_{\text{st.}}|\text{-N}_{\text{con.}} = 2.$$

4. The task completion score is calculated $K \in [0;1]$:$\text{K} = \frac{\text{N}_{\text{con.}}}{\text{N}_{\text{tr.}}+\text{N}_{\text{def.}}} = \frac{3}{4+2} = 0{,}5$ (i.e. the student built the left part, the restrictions are 50% correct).

It follows from the examples above, for exercises on the development and analysis of mathematical models of optimization problems using the training and education subsystem of intelligent training complexes, automatic assessment of the correctness of execution is carried out, which allows reducing the time spent on assessing exercises by the teacher and waiting for the assessment by the student, reducing the degree of subjectivity that occurs when checking the solution by the teacher.

4 Conclusion

A method has been developed for a comprehensive assessment of the quality of performing exercises on optimization problems in the virtual environment of intelligent training complexes. The method differs from the known ones in many parameters that determine the structure and specificity of these problems, and is also formalized on the basis of fuzzy sets that describe incomplete knowledge when comparing the mathematical model of the problem created by the student with the reference one.

The use of intelligent training complexes, in the software of which the presented method is implemented, will allow for ongoing monitoring and self-monitoring of students' knowledge and skills when studying disciplines in the field of development of mathematical support for automated control systems for production processes (and related disciplines in the field of mathematical methods in the food industry). The use of intelligent training complexes ensures the collection and analysis of data on the dynamics in the formation of professional knowledge and skills among students in the development of mathematical software for automated control systems.

The use of the developed method for assessing the performance of exercises in intelligent training complexes for the construction and analysis of mathematical models of optimization problems increases the objectivity of monitoring the skills of solving such problems in comparison with the "manual" assessment by the teacher of their implementation. Accordingly, the time for conducting control activities for the teacher is reduced, and the accuracy of the results of monitoring the formation of students' knowledge and skills is increased.

The study was carried out with financial support from the Russian Science Foundation within the framework of scientific project No. 23-79-10162.

References

1. I.S. Polevshchikov, R.A. Kravchenko, E3S Web of Conferences **443,** 06011 (2023) https://doi.org/10.1051/e3sconf/202344306011
2. T.B. Chistyakova, D.N. Furaev, A computer system for training of specialists in design of industrial facilities for petrochemistry and oil processing *Proceedings of 2018 17th Russian Scientific and Practical Conference on Planning and Teaching Engineering*

Staff for the Industrial and Economic Complex of the Region PTES 2018 (Institute of Electrical and Electronics Engineers Inc., 2019) pp. 92-94
3. V.M. Dozortsev, D.V. Agafonov, V.A. Nazin, et al., Automation and Remote Control **81(5)** 935-954 (2020)
4. L.S. Lisitsyna, M.S. Senchilo, E.A. Efimchik, Smart Innovation, Systems and Technologies **188** 171-180 (2020)
5. L. Tomczyk, K. Potyrala, N. Demeshkant, K. Czerwiec, University teachers and crisis e-learning: results of a polish pilot study on: attitudes towards e-learning, experiences with e-learning and anticipation of using e-learning solutions after the pandemic *Iberian Conference on Information Systems and Technologies, (CISTI)* In: Proceedings of CISTI 2021 - 16th Iberian Conference on Information Systems and Technologies, 2021
6. N. Gracelita, L.R. Maghfiroh, Journal of Physics: Conference Series **1511(1)** 012020 (2019)
7. S.R.M. Zeebaree, A. Al-Zebari, K. Jacksi, A. Selamat, Journal of Advanced Research in Dynamical and Control Systems **11(5)** 24-37 (2019)
8. A. Gero, Y. Stav, I. Wertheim, A. Epstein, Global Journal of Engineering Education **21(2)** 139-144 (2019)
9. M.M. Blagoveshchenskaya, I.S. Polevshchikov, E.R. Ponasenkov, R.A. Kravchenko, AIP Conference Proceedings, **2627,** 070001 (2023) https://doi.org/10.1063/5.0135984
10. I.S. Polevshchikov, A.P. Rozhkov, G.A. Ilyin, Engineering Bulletin of the Don **10 (**2022) URL: ivdon.ru/ru/magazine/archive/n10y2022/7916