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Mathematical and software support for the automated knowledge control subsystem of process plant operators on a training complex

Ivan Polevshchikov[1,2,3*], *Sergey* Mokrushin[1], *Vladimir* Nedvetsky[1], and *Maksim* Dmitruk[2]

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

Abstract. This study focuses on the development of automated knowledge control systems for process plant operators based on computer training complexes. Functional requirements for the complex subsystem for automated knowledge control of production process operators have been developed. The subsystem allows instructors not only to manually create sets of test tasks but also to configure knowledge about the subject area of operators' professional activities for automatic generation of a required number of test tasks of a specific type and complexity level. A method for modeling the subject area has been developed to conduct automated testing of knowledge on safety rules when working with equipment and the sequence of actions during the operation of production equipment. An algorithm has been developed to evaluate the result of performing a test task on establishing the sequence of operator actions when working on a process plant. This algorithm allows for a detailed comparison of the reference result of the task, automatically generated based on the subject area settings, with the trainee's result. A prototype of the software for the computer complex automated knowledge control subsystem has been developed as a web application based on the described mathematical models and algorithms.

1 Introduction

In the process of professional training for production process operators (particularly in the food industry and agro-industrial complex), trainees are required to master knowledge and skills in the area of safe and quality work on technological equipment [1].

Computer training complexes (CTC) used for operator training allow for: initial control of knowledge and skills on required topics within the theoretical training course (specifically, knowledge of safety rules for equipment operation, sequence of actions when performing various tasks using equipment); control of skills in performing technological processes on equipment through exercises [2-4].

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

A drawback in organizing the control process in CTC and other similar automated information systems (particularly Moodle [5-7]) used in the educational process is the need to spend time compiling sets of a sufficient number of test tasks to form unique test variants for each trainee.

2 Method for modeling the subject area of operators' professional activities for automated knowledge control

Functional requirements for the CTC subsystem for automated knowledge control of production process operators have been developed, as shown in the Use Case UML diagram in Figure 1.

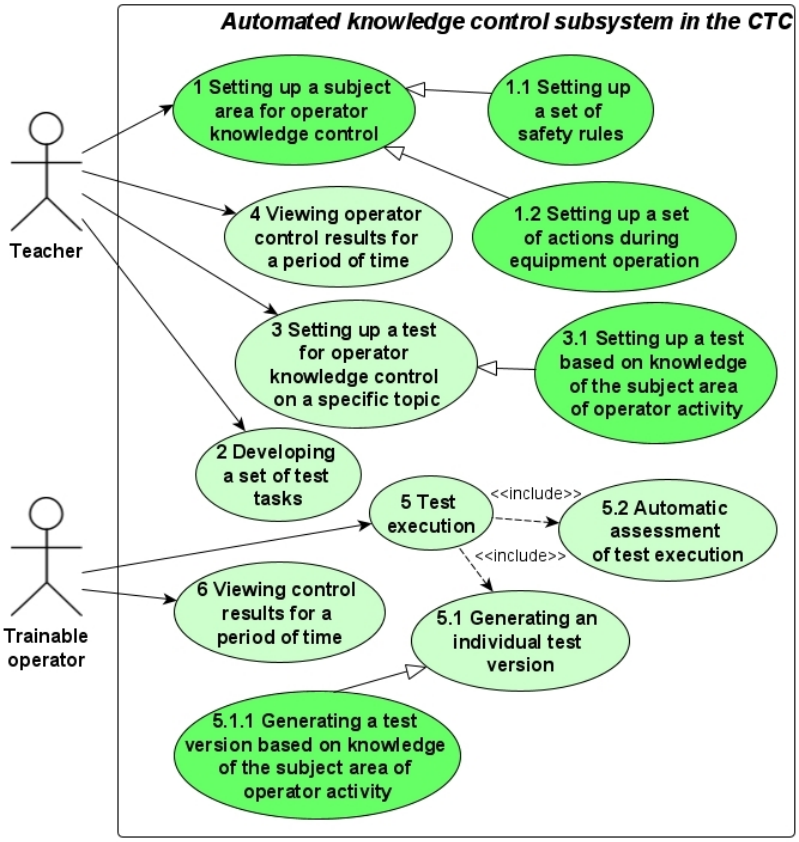

Fig. 1. Functional capabilities of the CTC testing subsystem.

As Figure 1 shows the subsystem provides the instructor with the ability to not only manually create sets of test tasks but also to configure knowledge about the subject area of operators' professional activities. This allows for automatic generation of a required number of test tasks of a specific type (with the selection of one correct answer, multiple correct answers, sequence establishment, etc.) and complexity level.

Based on the development of scientific research [8], a methodology has been developed for modeling the subject area of operators' professional activities for automated compilation of test tasks. These tasks check knowledge of safety rules when using equipment, as well as the sequence of actions when performing various operations during equipment operation.

Modeling the subject area for conducting automated testing of knowledge of safety rules when working with equipment includes the following components:

1. Let the set of safety rules for operating a process plant, which will be used for knowledge assessment in the form of testing, be represented as $A_{\text{rul.}} = \left\{a_i^{\text{rul.}} | i = \overline{1, N_{\text{rul.}}}\right\}$, where $a_i^{\text{rul.}}$ – separate rule, $N_{\text{rul.}}$ – total number of rules.
2. Each i -th rule can be correspondent to the template $B_i^{\text{tmp.}}$ of the test task: $B_i^{\text{tmp.}} = \{a_i^{\text{tr.}}\} \cup C_i^{\text{tmp.}}$ – many correct and incorrect formulations of safety rules, where$a_i^{\text{tr.}}$is the correct formulation of safety rules, $C_i^{\text{tmp.}} = \left\{a_{ij}^{\text{fls.}} | j = \overline{1, N_{\text{fls.}}}\right\}$ – a subset of incorrect wording of safety regulations, $a_{ij}^{\text{fls.}}$ – incorrect wording of safety rule, $N_{\text{fls.}}$ – total number of incorrect formulations. As a result, a set of patterns $M_{\text{tmp.}} = \left\{B_i^{\text{tmp.}} | i = \overline{1, N_{\text{rul.}}}\right\}$ is defined.
3. 3. The test parameters are configured, which are generally represented by a set $M_{\text{set.}} = \left\{x_{\text{typ.}}, x_{\text{tsk.}}, x_{\text{cnt.}}^{min}, x_{\text{cnt.}}^{max}, x_{\text{var.}}^{min}, x_{\text{var.}}^{max}\right\}$, where $x_{\text{typ.}}$ is the type of the task in the test ($x_{\text{typ.}} = 0$ – choice of one variant of the answer, $x_{\text{typ.}} = 1$ – choice of several answers to the test); $x_{\text{tsk.}}$ – method for determining the number of tasks in a test ($x_{\text{tsk.}} = 0$ – the number of tasks is set manually, $x_{\text{tsk.}} = 1$ – the number of tasks is set automatically taking into account the minimization of the probability of guessing the correct answers); $x_{\text{cnt.}}^{min}$ and $x_{\text{cnt.}}^{max}$ – minimum and maximum number of tasks in the test; $x_{\text{var.}}^{min}$ and $x_{\text{var.}}^{max}$ – minimum and maximum number of answer options in a test task.
4. Based on the settings, an individual version of the test is formed for each student. In general, the structure of the test is represented by a set $M_{\text{tst.}} = \left\{m_r^{\text{tst.}} | r = \overline{1, N_{\text{tst.}}}\right\}$, where $m_r^{\text{tst.}}$ – separate test task, $N_{\text{tst.}}$ – number of tasks in the test. Multiple choice answers in a test task $m_r^{\text{tst.}}$ in general is defined as $D_r = \bigcup_{i=1}^{N_{\text{rul.}}} E_i^{\text{tmp.}}$, where $E_i^{\text{tmp.}} \subseteq B_i^{\text{tmp.}}$. Let us assume the case of an empty subset as $E_i^{\text{tmp.}} \equiv \emptyset$.

Modeling of the subject area for conducting automated testing of knowledge regarding the sequence of actions during the operation of production equipment includes the following components:

1. The set of actions that an operator must perform during the operation of production equipment is represented by $C_{\text{eqp.}} = \left\{c_i^{\text{eqp.}} | i = \overline{1, N_{\text{eqp.}}}\right\}$, where $c_i^{\text{eqp.}}$ – separate action, $N_{\text{eqp.}}$ – total number of actions. For example, $C_{\text{eqp.}} = \{c_1, c_2, c_3, c_4, c_5\}$.
2. The correct sequence of actions can be represented by the relation $R_{\text{tr.}} \subseteq C_{\text{eqp.}} \times C_{\text{eqp.}}$. For example, $R_{\text{tr.}} = \{\langle c_1, c_2\rangle, \langle c_2, c_3\rangle, \langle c_3, c_4\rangle, \langle c_4, c_5\rangle\}$.
3. The test parameters are configured, which are generally represented by a set $M_{\text{set.}}^{'} = \left\{x_{\text{typ.}}, x_{\text{tsk.}}, x_{\text{cnt.}}^{min}, x_{\text{cnt.}}^{max}, x_{\text{var.}}^{min}, x_{\text{var.}}^{max}\right\}$, where $x_{\text{typ.}}$ – type of task in the test ($x_{\text{typ.}} = 0$ – choice of one answer, $x_{\text{typ.}} = 1$ – setting sequence). Parameters $x_{\text{tsk.}}$, $x_{\text{cnt.}}^{min}$, $x_{\text{cnt.}}^{max}$, $x_{\text{var.}}^{min}$, $x_{\text{var.}}^{max}$ are similar to those described above for the set $M_{\text{set.}}$.
4. Based on the settings, an individual version of the test is formed for each student. In general, the structure of the test is represented by a set $M_{\text{tst.}}^{'} = \left\{h_k^{\text{tst.}} | k = \overline{1, N_{\text{tst.}}^{'}}\right\}$, where $h_k^{\text{tst.}}$ – separate test task, $N_{\text{tst.}}^{\prime}$ – number of tasks in the test. Multiple choice answers in a test task $h_k^{\text{tst.}}$ in general can be defined as $V_k \subseteq C_{\text{eqp.}}$.

Various algorithms for evaluating test tasks in the process of operators' knowledge control are permissible. An algorithm for assessing the result of performing a test task to establish the sequence of operator actions when working on a process plant has been developed, based on a set-theoretic approach [8]:

1. The result of the correct determination of the sequence of actions is represented by a

set $R_{\text{tr.}}$. In the example under consideration, for a set of actions in a sequence $C_{\text{eqp.}} = \{c_1, c_2, c_3, c_4, c_5, c_6\}$ the relation $R_{\text{tr.}}$ will be presented as:
$R_{\text{tr.}} = \{\langle c_1, c_2\rangle, \langle c_2, c_3\rangle, \langle c_3, c_4\rangle, \langle c_4, c_5\rangle, \langle c_5, c_6\rangle\}$.

2. The result of determining the sequence of actions by the trainee is represented by a set: $R_{\text{st.}} = \{\langle c_2, c_3\rangle, \langle c_3, c_4\rangle, \langle c_4, c_6\rangle, \langle c_6, c_5\rangle, \langle c_5, c_1\rangle\}$.
3. The parameters of the relationship correspondence $R_{\text{tr.}}$ and $R_{\text{st.}}$ are calculated:
$N_{\text{tr.}} = |M_{\text{tr.}}| = 5$;
$R_{\text{tr.}} \cap R_{\text{st.}} = \{\langle c_2, c_3\rangle, \langle c_3, c_4\rangle\}$;
$\text{N}_{\text{con.}} = |\text{R}_{\text{tr.}} \cap \text{R}_{\text{st.}}| = 2$;
$\text{N}_{\text{def.}} = |\text{M}_{\text{st.}}|\text{-N}_{\text{con.}} = 5\text{-}2 = 3$.
4. The dimensionless estimate $K_{\text{seq.}} \in [0; 1]$ is calculated performing an exercise to establish a sequence of actions:

$\text{K}_{\text{seq.}} = \frac{\text{N}_{\text{con.}}}{\text{N}_{\text{tr.}}+\text{N}_{\text{def.}}} = \frac{2}{5+3} = 0{,}25$ (i.e., the trainee established the correct sequence of actions only by 25%).

The developed algorithm allows obtaining an assessment of task performance not only on a "correct" or "incorrect" scale but also on a 100-point scale, which contributes to a more accurate evaluation of the dynamics of professional knowledge acquisition by trainee operators.

3 Results of the development of the subsystem of automated knowledge control of the CTC

The prototype of the software for the automated knowledge control subsystem of the CTC has been developed as a web application based on the mathematical models and algorithms described above.

Figure 2 shows the web interface of the CTC for working with a set of safety rules for equipment operation.

No	Safety Rule
1 + ✎ ×	During the work cycle with the control system on, it is prohibited to open the control panel.
2 + ✎ ×	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 50°C.
3 + ✎ ×	The operator must monitor the pressure and temperature level both on the operator panel and on stationary devices near the autoclave.

Add a rule

Fig. 2. Web interface for working with a variety of safety regulations.

Selecting the icon in the form of a "plus" symbol or the "Add rule" link in the interface shown in Figure 2 leads to the configuration of the test task template that checks the knowledge of the given rule (Figure 3). The template configuration includes defining one correct and several incorrect formulations of the rule, which will later be used in the testing process as answer options.

No	Correct wording	Safety rule formulation
1 + ✎ ×	◉	During the work cycle with the control system on, it is prohibited to open the control panel.
2 + ✎ ×	○	During the work cycle with the control system on, it is permitted to open the control panel.
3 + ✎ ×	○	During the work cycle with the control system on, it is necessary to open the control panel.

Add a wording

Fig. 3. Web interface for setting up a test task template (for rule #1).

An example of configuring a test task template with a large number of answer options (for rule 2 from Figure 2) is shown in Figure 4.

No	Correct wording	Safety rule formulation
1 + ✎ ×	○	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 70°C.
2 + ✎ ×	○	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is above 70°C.
3 + ✎ ×	◉	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 50°C.
4 + ✎ ×	○	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is above 30°C.
5 + ✎ ×	○	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 10°C.

Add a wording

Fig. 4. Web interface for setting up a test task template (for rule #2).

The configuration of a test assessing knowledge of safety procedures for equipment operation on a specific topic is carried out through the web interface shown in Figure 5. Test configuration includes setting the task type (single or multiple choice), task formulation (by clicking the "pencil" icon, it is possible to modify the standard formulation to better suit the test topic), the number of tasks in the test, and the number of answer options per task. It is permissible to use checkboxes to mark safety rules that will not be included in this version of the test.

Type of tasks	◉ select one answer option ○ select multiple answers
Formulation of the task in the test	◉ Select the correct wording of the safety rule for using an autoclave in the process of sterilizing canned food. ✎ ○ Select the NOT correct wording of the safety rule for using an autoclave in the process of sterilizing canned food. ✎
One task in the test can be related to	◉ only one safety rule ○ several safety rules
Number of tasks in the test	◉ from 4 to 5 ○ automatic determination of the number of tasks *(taking into account the minimization of the probability of guessing the answers)*
Number of answer options in the task	from 3 to 4

What rules to include in the test:

	No	Safety Rule
☑	1 + ✎ ×	During the work cycle with the control system on, it is prohibited to open the control panel.
☑	2 + ✎ ×	After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 50°C.
☐	3 + ✎ ×	The operator must monitor the pressure and temperature level both on the operator panel and on stationary devices near the autoclave.

Fig. 5. Web interface for setting up a test according to safety regulations (first variation of the setting).

Figure 5 shows a set of settings for a test consisting of several questions with the option to select only one answer using a group of radio buttons. The web interface for completing a test task with a single answer choice, generated according to the settings in Figure 5, is presented in Figure 6.

Select the correct wording of the safety rule for using an autoclave in the process of sterilizing canned food.
Select one correct answer from the suggested ones:
⦿ After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 50°C.
○ After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 70°C.
○ After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is above 70°C.
○ After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 10°C.

Fig. 6. Web interface for completing a test task on safety engineering with a choice of one answer option.

Figure 7 shows the set of settings for a safety rules test consisting of one question with the option to select multiple answers using checkboxes.

Type of tasks	○ select one answer option ⦿ select multiple answers
Formulation of the task in the test	⦿ Select the correct wording of the safety rule for using an autoclave in the process of sterilizing canned food. ○ Select the NOT correct wording of the safety rule for using an autoclave in the process of sterilizing canned food.
One task in the test can be related to	○ only one safety rule ⦿ several safety rules
Number of tasks in the test	⦿ from 1 to 1 ○ automatic determination of the number of tasks *(taking into account the minimization of the probability of guessing the answers)*
Number of answer options in the task	from 5 to 6

Fig. 7. Web interface for setting up a test according to safety regulations (second variation of setting up).

The web interface for completing a multiple-choice test task, generated according to the settings shown in Figure 7, is presented in Figure 8.

Select the correct wording of the safety rule for using an autoclave in the process of sterilizing canned food.
Select one or more correct answers from the suggested ones:
☐ During the work cycle with the control system on, it is permitted to open the control panel.
☑ After completing the work, the autoclave lid may be opened only when the temperature in the autoclave is below 50°C.
☐ During the work cycle with the control system on, it is permitted to open the autoclave lid.
☑ The operator must monitor the pressure and temperature level both on the operator panel and on stationary devices near the autoclave.
☐ The operator is not obliged to inform the manager about the accident.

Fig. 8. Web interface for completing a test task on safety engineering with multiple choice answers.

The configuration of the test on knowledge of the sequence of actions during equipment operation is performed in the interface shown in Figure 9. A specific case of configuration is presented, where the trainee is required to answer a series of questions with a single choice of answer, generated according to the established correct sequence of actions. In the lower

part of the interface (Figure 9), it is possible to add, delete, edit actions, and change their order using the corresponding icons.

Type of tasks	○ setting the sequence of actions ⊙ choosing one answer option
Formulation of the task in the test	○ Set the correct sequence of actions when working with an autoclave. ⊙ Select the action immediately preceding the action: ○ Select the action immediately following the action:
Number of tasks in the test	⊙ from 3 to 3 ○ automatic determination of the number of tasks *(taking into account the minimization of the probability of guessing the answers)*
Number of answer options in the task	from 3 to 4

What actions to include in the test:

	No	Sequence of actions
☑	1 + × ↑↓	When the panel is operating, press the preparatory mode on-screen button on the first startup screen.
☑	2 + × ↑↓	The autoclave will begin preparing for operation.
☑	3 + × ↑↓	The autoclave will be heated to 50°C.
☑	4 + × ↑↓	The system will go to the sterilization formula input screen.
☑	5 + × ↑↓	Confirm the entered sterilization formula with the button.
☐	6 + × ↑↓	The panel will go to the startup screen and wait until the autoclave is loaded and closed.
☐	7 + × ↑↓	Start the main mode by pressing the corresponding button on the operator panel.

Fig. 9. Web interface for setting up a test of knowledge of the sequence of actions (first variation of the setting).

The web interface for completing a test task on knowledge of the sequence of actions with the selection of one correct answer, generated according to the settings in Figure 9, is shown in Figure 10.

Select the action immediately preceding the action: Confirm the entered sterilization formula with the button.
Select one correct answer from the suggested ones:
○ Start the main mode by pressing the corresponding button on the operator panel.
○ The autoclave will be heated to 50°C.
○ The panel will go to the startup screen and wait until the autoclave is loaded and closed.
⊙ The system will go to the sterilization formula input screen.

Fig. 10. Web interface for completing a test task on knowledge of the sequence of actions with a choice of one answer option.

Figure 11 illustrates a specific configuration case where the trainee operator is required to establish the correct order of the sequence of actions for a particular topic.

Type of tasks	⊙ setting the sequence of actions ○ choosing one answer option
Formulation of the task in the test	○ Set the correct sequence of actions when working with an autoclave. ⊙ Select the action immediately preceding the action: ○ Select the action immediately following the action:
Number of tasks in the test	⊙ from 1 to 1 ○ automatic determination of the number of tasks *(taking into account the minimization of the probability of guessing the answers)*
Number of answer options in the task	from 5 to 5

Fig. 11. Web interface for setting up a test of knowledge of the sequence of actions (second variation of the setting).

The web interface for performing the test task on establishing the sequence of actions, generated according to the settings shown in Figure 11, is presented in Figure 12. The trainee operator establishes the correct sequence of actions, from their perspective, using the "up arrow" and "down arrow" icons.

Set the correct sequence of actions when working with an autoclave.	
Set the correct sequence of actions by selecting the "up" and "down" arrows:	
↑↓	The autoclave will be heated to 50°C.
↑↓	When the panel is operating, press the preparatory mode on-screen button on the first startup screen.
↑↓	The autoclave will begin preparing for operation.
↑↓	Confirm the entered sterilization formula with the button.
↑↓	The system will go to the sterilization formula input screen.

Fig. 12. Web interface for performing a test task to set up a sequence of actions.

The application of the above-described CTC subsystem in the educational process provides: flexible test configuration depending on the adopted training methodology; test execution by trainee operators; automatic verification of test results; storage of test results in the CTC database with the ability to view them in a visual format through a web interface.

4 Conclusion

Functional requirements for the Computer Training Complex (CTC) subsystem for automated knowledge control of process plant operators have been developed and formally presented using a UML Use Case diagram. The subsystem allows instructors not only to manually create sets of test tasks but also to configure knowledge about the subject area of operators' professional activities for automatic generation of a required number of test tasks of a specific type (with single correct answer selection, multiple correct answers, sequence establishment, etc.) and complexity level.

A method for modeling the subject area has been developed to conduct automated testing of knowledge on safety rules when working with equipment and the sequence of actions during the operation of production equipment. The method is based on a set-theoretic approach in describing the subject area, test process settings, and test task structure. An algorithm has been developed to evaluate the result of performing a test task on establishing the sequence of operator actions when working on a process plant. This algorithm allows for a detailed comparison of the reference result of the task, automatically generated based on the subject area settings, with the trainee's result to obtain a score on a 100-point scale.

A prototype of the software for the CTC automated knowledge control subsystem has been developed as a web application based on the described mathematical models and algorithms. Web interfaces for instructor and student personal accounts have been presented. The application of the CTC subsystem in the educational process provides: flexible test configuration depending on the adopted training methodology; test completion by trainee operators; automatic verification of results; storage of test results in the CTC database with the ability to view them in a clear format in the web interface.

The CTC, based on the developed models, algorithms, and software modules, can be practically applied in organizations that train process operators, including on-the-job training.

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