UDC 004.421.2 **doi: 10.32620/reks.2025.2.01**

Rustam TOGAMBAYEV[1], Ildar PIRMANOV[2], Kayrat KOSHEKOV[2], Nataliia LEVCHENKO[3], Abay KOSHEKOV[2], Yuri TANOVITSKIY[2], Yakub KURBANOV[2]

[1] ***Transport and Telecommunication Institute, Latvia***
[2] ***Civil Aviation Academy, Republic of Kazakhstan***
[3] ***Technical University of Berlin, Germany***

DIGITALIZATION OF THE EDUCATIONAL PROCESS: SYNERGY OF GAMIFICATION AND ARTIFICIAL INTELLIGENCE IN THE TRAINING OF HIGHLY QUALIFIED CIVIL AVIATION SPECIALISTS

The subject matter *of this article presents the results of a study on the digital transformation of the educational process of training highly qualified air transport specialists, as well as retraining and advanced training of civil aviation employees to acquire the necessary competencies to ensure flight safety and high-quality passenger service at airports. It is emphasized that simulation, virtual reality, and artificial intelligence technologies have been actively integrated into the educational process of higher education institutions in recent years and have proven the feasibility of their use. However, their use in the corporate training of aviation employees is complicated by several obstacles. Among these, first, attention should be paid to the correctness of assessing the competencies acquired by employees, which is extremely necessary when making decisions on their certification.* ***The goal*** *– to substantiate, based on the results of the experiment, the feasibility of using immersion technologies based on the synergy of gamification and artificial intelligence in corporate training of civil aviation employees, which will ensure the interactivity of the educational process, its constructivism, and implementation according to a practice-oriented approach, as well as the realism of the assessment of the competencies acquired by the personnel for their subsequent certification by international standards.* ***Results****. Guided by the requirements of international standards, particularly for the performance of aircraft anti-icing work, a model for assessing the competencies acquired by employees due to advanced training in the correctness of aircraft anti-icing has been developed. This assessment model is based on fuzzy logic, which allows processing parameters with fuzzy limits and realistically assesses the quality of the anti-icing procedure. The construction methodology is based on the fuzzy phasing of input variables, building a rule base, and defuzzification to obtain a final assessment.* ***Conclusions****. The study results proved the feasibility of using immersion technologies in the corporate training of civil aviation employees. They developed a model for assessing the competencies they had acquired, which allowed for a realistic assessment of airline employees' acquired knowledge and skills and, accordingly, certifying them by international standards.*

Keywords: *digital transformation of the educational process; immersive learning technologies; gamification; gamified learning; artificial intelligence.*

1. Introduction

1.1. Motivation

The digitization of modern society is spreading into new areas of activity. Education is no exception. In this context, along with traditional educational approaches, immersion technologies – gamification, virtual reality (VR), and artificial intelligence (AI) technologies – are increasingly being used. Their wide integration into the field of education contributes to the mutual complementarity of the applied educational paradigms aimed at training highly qualified specialists [1], the shortage of which is especially noticeable in civil aviation, both in the countries of the world and, in particular, in the Republic of Kazakhstan.

It should be noted that civil aviation in Kazakhstan is one of the fastest-growing industries in the country. Currently, there are 56 airlines registered in the Republic of Kazakhstan [2], transporting 14.3 million passengers in 2024 and serving 29.7 million people at airports. In 2024 alone, domestic airlines acquired 11 aircraft, increasing the fleet's capacity by 28% to 15.4 thousand seats [3].

Shortly, the growth rate of air transportation by domestic aviation will only increase because the geographical location of Kazakhstan will allow it to serve as an essential link between Europe and China. Therefore, the growing demand for air transportation in China

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

and other Asian countries will continue to contribute to the active development of Kazakhstan's aviation industry [4]. Currently, the created fleet allows Kazakhstan's aviation to increase the number of routes, but the growing shortage of aviation specialists from year to year significantly complicates this process [5].

According to the Ministry of Transport of the Republic of Kazakhstan, approximately 23,000 people currently work in civil aviation [6]. At the same time, the annual shortage of personnel in aviation enterprises amounts to more than 0.5-0.6 thousand people. This scale is increasing every year.

The Civil Aviation Academy of Kazakhstan (Academy) has trained aviation specialists in the country for a long time. It is expected that an audit conducted shortly by the European Aviation Safety Agency (EASA) will allow the Academy to receive a certificate confirming the high level of training of civil aviation specialists and thus reduce the proportion of foreign specialists (in particular pilots) attracted by airlines [7].

1.2. State of the art

The Academy is creating a modern aviation-training center that meets European standards for training pilots and engineers under the EASA PART-FCL programs for licensing pilots and EASA PART-66/147 to obtain a license to perform aircraft maintenance work. In addition, the Academy Roadmap includes measures to digitalize the educational process fully [8]. The training of highly qualified aviation specialists requires extensive theoretical knowledge and the acquisition of practical skills, making the use of immersion technologies particularly relevant in the educational process.

It is essential to understand that even the most modern aircraft with high-tech control systems cannot guarantee flight safety without well-trained specialists [9]. Therefore, Academies actively integrate gamification, VR, and AI technologies into education. Their use allows for the simulation of alternative spaces with the possibility of full or partial immersion of students in a given environment, which ensures the interactivity of the educational process, its constructivism, and implementation according to a practice-oriented approach.

With the use of gamification and AI technologies in the educational process, students have acquired the opportunity to use pre-prepared learning tools and independently form an idea of the environment in which they will conduct professional activities. AI can offer students a personalized educational path that optimizes and enhances learning. Combined with instant feedback and step-by-step instructions, immersion technologies act as highly qualified and flexible private tutors, with an endless bank of information and tasks adapted to students with different levels of intelligence, communication and knowledge acquisition rates. This practice significantly increases students' academic potential with substantially less time investment [10].

The use of immersion technologies in the educational process, as evidenced by their practice, is accompanied by a positive effect [11]. However, their use in corporate training (retraining or advanced training) of aviation enterprise personnel has specific problems, the search for solutions to which is carried out in this study.

A review of the literature. In recent years, the education sector has undergone several radical changes, which have affected all participants in the educational process [12]. In particular, during the COVID-19 pandemic, teaching had to be transferred to the online mode [13], which led to the integration of innovative technologies and teaching methods into education [14], which, as it turned out, opened up new opportunities for transforming and enriching the educational process [15]. In particular, online education has contributed to creating an effective learning environment, flexibility, responsibility, and active participation among students without direct and constant supervision by teachers [16]. Gamification technologies involving game elements in learning have accelerated the transformation and enrichment of educational processes, activating students' involvement and motivation to learn. Motivation, as we know, is a vital element [17] because it contributes to effective learning and the achievement of better results [18, 19].

Therefore, the use of gamification technologies in the educational process should be recognized as a practical innovative approach in education, the advantages of which over traditional teaching technologies are visible in the publications of scientists such as Poluru N. [20]; Kim, J. and Castelli, D. [21]; Pozo-Sánchez, S., Lampropoulos, G., López-Belmonte, J. [22]; Lampropoulos et al. [14]; Kaufmann, D. [23]; Marín, B. et al [24].

Gamification makes it possible to create personalized educational programs and encourage enthusiasm in their implementation. It promotes the development of communication skills and social responsibility, friendly competition and cooperation [25], and improving inclusive education [26], in particular, by creating a specific learning style and providing students with individual support when needed [27].

In symbiosis with technologies such as AI, content generation, automated assessment, automated management, and others, gamification has an inexhaustible potential to create [28] a more engaging [29], personalized [17], and effective learning environment. Therefore, gamification and AI technologies are actively introduced by Kazakhstan's airlines in their employees' training, retraining and advanced training [30].

However, gamification has disadvantages [31, 32].

Among these, the most attention-grabbing is the need to constantly revise methods of assessing acquired knowledge and competencies. In educational training, this issue is solved much more easily [33] than in corporate training of airline personnel because there are now many applications for online knowledge assessment. These are popular and easily accessible. At the same time, each application has standard and unique features [34], which makes it very difficult to select the best application for knowledge assessment. This problem in the corporate training of airlines remains unsolved and requires further research [35].

1.3. Objectives and approach

The object of this study is to substantiate, based on the results of the experiment, the feasibility of using immersion technologies based on the synergy of gamification and artificial intelligence in the corporate training of civil aviation employees, which will ensure the interactivity of the educational process, its constructivism, and implementation using a practice-oriented approach, as well as the realism of the assessment of the competencies acquired by the personnel for their subsequent certification by international standards.

Based on the stated objective, the main **tasks** of this study were as follows:

- based on the experiment results, substantiate the feasibility of using gamification technologies in symbiosis with artificial intelligence in civil aviation personnel's corporate training (retraining and advanced training);
- guided by the methodology of fuzzy logic, to develop a model for assessing the knowledge and skills acquired by airlines' personnel in performing aircraft anti-icing procedures, the application of which in practice will allow establishing the level of compliance of competencies with the requirements of international standards;
- visualize the experiment's results by assessing the knowledge and skills acquired by the students in performing the anti-icing procedure, which will allow for determining the zones of optimal parameters, identifying risk areas, and drawing conclusions about the level of competencies acquired by them.

The article is structured as follows.

Section 1 discusses the motivation behind this study. It also provides an overview of the state of digitalization of education with a focus on the use of immersive technologies such as gamification, virtual reality and artificial intelligence. The application of these technologies is especially relevant in the training of highly qualified specialists in civil aviation in the Republic of Kazakhstan, which is experiencing a shortage of skilled personnel against the background of rapid growth of the industry.

Section 2 describes the materials used in this study, as well as a set of research methods and the stages of their application.

Section 3 presents the stages and results of the conducted experiment to assess the competences acquired by the personnel to perform work on aircraft anti-icing. The expediency of applying immersion technologies based on the synergy of gamification and artificial intelligence in the corporate training of civil aviation employees is proven, which will ensure the interactivity of the educational process, its constructivism and implementation of a practice-oriented approach.

Section 4 presents a discussion of the existing methods of assessment of competences acquired by the trainees, emphasizing their advantages and disadvantages, the possibility and expediency of their scaling in the educational process of higher educational institutions and corporate training; substantiates the advantages of the author's methodology based on fuzzy logic, which, due to the phasing of parameters and fuzzy rules, provides flexibility in decision-making and allows the instructor or automated system to form recommendations for improvement.

Section 5 presents conclusions based on the results of the study and reveals the practical significance of the author's methodology of assessment of competences acquired by the students and outlines the directions of further research on this subject within the framework of the Project under the grant of the Science Committee of the Ministry of Science of the Republic of Kazakhstan No. AP19680080 ‘Development of a training complex with a system of engineering support for the technical operation of military and special aviation transport equipment’.

2. Materials and methods of research

To study the effectiveness of immersion training technologies, the Civil Aviation Academy conducted a series of experiments to assess the competencies acquired by students based on the results of educational and corporate training. The experiment involved students from the Academies and employees of the ground handling companies of the Kazakhstan air fleet. The anti-icing procedure of the aircraft was chosen to conduct an experiment to assess the competencies acquired by students. The fundamental basis for this choice was, first, the relatively high labour and material costs of developing the skills to perform this procedure of ground handling by airliners.

The fuzzy logic method was used to develop the assessment model for students' acquired knowledge and skills in performing the anti-icing procedure, which allows the processing of parameters with fuzzy limits.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

The methodology for constructing this model is based on the fuzzy phasing of input variables, building a rule base, and defuzzification to obtain the final assessment. During the experiment, nine key input parameters were defined to characterize the anti-icing process (execution time, liquid consumption, uniformity of coating, etc.), and one output variable was defined to assess the procedure's correctness. Each input variable is described using triangular membership functions to ensure a smooth transition between fuzzy states. The assessment rule based on expert knowledge made it possible to determine the relationship between the anti-icing procedure parameters and the final assessment.

A scikit-fuzzy library in the Python environment was used to implement the model, which created a fuzzy control system, automated calculations, and visualization of the results. The methodology included phasing the input data, applying the T-norm for the aggregation of rules, calculating each rule’s activity level, and applying the centroid defuzzification method to obtain the final assessment. Visualization of membership functions and contour plots of the relationship between variables allowed the evaluation of the influence of each of the parameters on the correctness of the anti-icing procedure. Thus, the developed model is a flexible and effective tool for assessing the competencies of air transport ground maintenance acquired by students.

3. Results

Researchers at the Civil Aviation Academy of Kazakhstan researched the use of gamification and AI technologies in the corporate training of airline personnel (in particular, in studying the correctness of performing work on the anti-icing procedure) within the framework of Project No. AP19680080 «Development of a training complex with a system of engineering support for the technical operation of military and special aviation transport equipment». The slightest mistake in performing this procedure is fraught with a threat to flight safety. Therefore, airlines regularly organize advanced training courses for air fleet ground-service employees to perform this procedure. The safety of flights largely depends on the correctness and quality of their implementation.

As noted earlier, training in implementing the anti-icing procedure of aircraft is quite a labour- and materially expensive because it requires students to acquire practical skills in performing these tasks. The way out of this situation is to use gamification technologies in the learning process, in symbiosis with AI technologies. AI technologies can create a bank of situations with varying complexities of performing the anti-icing procedure, and gamification technologies can create a virtual environment as close as possible to the real conditions of performing this procedure. The assessment of the acquired competencies in the correctness of performing anti-icing during this experiment was carried out using the fuzzy logic technique, which made it possible to process fuzzy and approximate the data characteristics of real conditions for performing the anti-icing procedure.

Based on the results of this study, a fuzzy model was developed to assess the competencies acquired by students in performing the aircraft anti-icing procedure based on the following key process parameters: execution time, fluid consumption, coating thickness, uniformity of application, compliance with regulations, ambient temperature, coating level, drying speed, and icing type. A fuzzy rules and fuzzy logic system was used in its construction.

Fuzzy logic is a mathematical apparatus that models uncertainty and processes fuzzy (ill-defined) parameters. Unlike traditional Boolean logic, which operates only on two states (yes or no), fuzzy logic allows one to determine the degree to which a value belongs to a specific category in the range of 0 to 1. This method is especially useful for processes in which it is impossible to unambiguously determine the correctness of an action, for example, in anti-icing processes, where the quality of aircraft processing depends on the interaction of many variables.

This solution is part of the Digital Twin (DT) concept of the aviation education process, which simulates real anti-icing conditions and allows students to adapt to real operational situations. A digital twin is a virtual reflection of a real process that enables the analysis of its effectiveness by testing different scenarios and predicting possible results. In our model, DT was used to assess students’ knowledge and skills in performing anti-icing procedures.

This approach allows the following:

- model various anti-icing conditions, including changes in temperature, icing level, and coating application speed;
- automatically analyzing errors and shortcomings in personnel actions based on fuzzy logic;
- individualizing training by adapting assessments to specific situations.

The process of constructing a fuzzy logic model consists of the following stages:

Stage 1. Identification of input (9) and output (1) variables:

$$X=\{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9\}, \qquad (1)$$

where:

x_1 – Execution Time (execution time, sec/min);
x_2 – Fluid Consumption (fluid consumption, litres);
x_3 – Coating Thickness (coating thickness, microns);

x_4 – Coating Uniformity (application uniformity, %);

x_5 – Technology Compliance (compliance with regulations, 0 or 1);

x_6 – Ambient Temperature (ambient temperature, °C);

x_7 – Coverage (coverage degree, %);

x_8 – Drying Speed (drying and flow rate, min);

x_9 – Icing Type (icing type: 1 – light, 2 – medium, 3 – heavy).

The output variable of the model is Evaluation (evaluation of the correctness of anti-icing):

$$y = f(X), \tag{2}$$

where f(X) is a fuzzy transformation that forms an assessment of the correctness of the anti-icing procedure.

Considering the uncertainty, each variable had fuzzy sets that allowed the system to analyze the anti-icing results.

Stage 2. Fuzzification (transformation of crisp values into fuzzy sets).

The following membership function describes each fuzzy set:

$$\mu_A(x) \in [0,1], \tag{3}$$

where μ_A (x) is a function that determines the degree of membership of a value *x* to a certain fuzzy set A.

We visualize the evaluation results using triangular (triangular, trim) activation functions. The main advantages of triangular functions are ease of use and speed of calculation.

Activation functions were defined for all nine inputs and one output variable to correctly model the aircraft anti-icing procedure.

An example of a triangular membership function for \"Execution Time\" is given below:

$$\mu_{fast}(x_1) = \left\{ \begin{array}{l} 0,\ x_1 \le 0 \text{ or } x_1 \ge 5; \\ \dfrac{x_1}{2.5},\ 0 < x_1 \le 2.5; \\ \dfrac{5\text{-}x_1}{2.5},\ 2.5 < x_1 < 5; \end{array} \right\} \tag{4}$$

Input Variables (for Airbus 321):

1. The execution time (task execution time, sec/min) characterizes how long it takes to complete the anti-icing procedure. The longer the procedure, the higher the probability of errors or ineffective fluid application.

Fuzzy sets: fast → (0–5 min); optimal → (4–10 min); long → (8–15 min); too long → (12–20 min). Figure 1 shows the activation functions for a variable that determines its fuzzy sets and the degree to which each value belongs to the corresponding category.

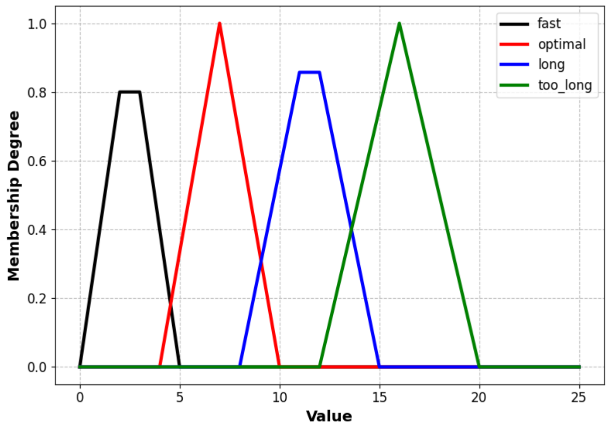

Fig. 1. Activation (membership) functions of the variable "Execution Time"

2. Fluid Consumption (fluid consumption, liters) characterizes the amount of fluid used during the procedure. Excessive or insufficient usage may result in incomplete protection against icing.

Fuzzy sets: Low (low consumption) → (100–300 l); optimal (optimal consumption) → (250–700 l); high (high consumption) → (650–1000 l).

Figure 2 shows the activation functions for a variable, defining its fuzzy sets and the degree to which each value belongs to the corresponding category.

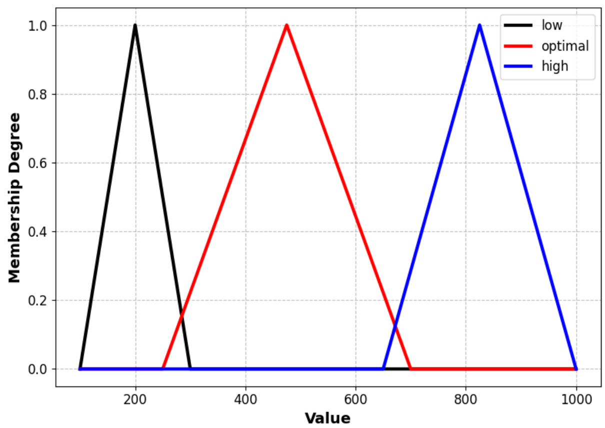

Fig. 2. Activation (membership) functions of the variable "Fluid Consumption"

3. Thickness (surface coating thickness, microns) characterizes the thickness of the applied layer of the anti-icing fluid. A coating that is too thin may be ineffective, excessively costly, and unstable.

Fuzzy sets: thin (thin) → (0–40 µm); optimal (optimal) → (35–60 µm); excessive (excessive) → (55–90 µm).

Figure 3 shows a variable's activation functions

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

that determine its fuzzy sets and the degree to which each value belongs to the corresponding category.

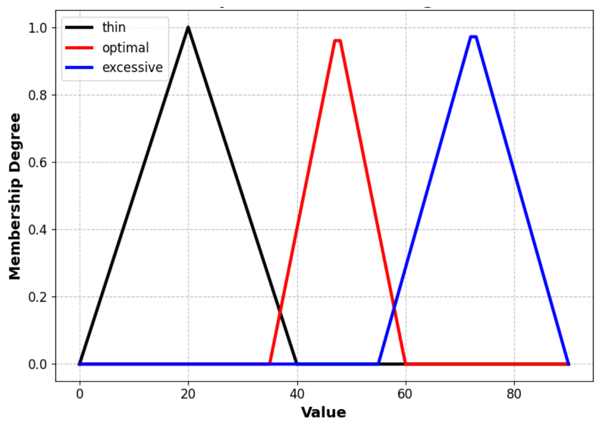

Fig. 3. Activation (membership) functions of the variable "Coating Thickness"

4. The coating Uniformity (uniformity of coating application, %) characterizes the uniformity of the anti-icing fluid applied.

Fuzzy sets: Low (low uniformity) → (0–60%); medium (medium uniformity) → (50–80%); high (high uniformity) → (75–100%).

Figure 4 shows the activation functions for a variable that determines its fuzzy sets and the degree to which each value belongs to the corresponding category.

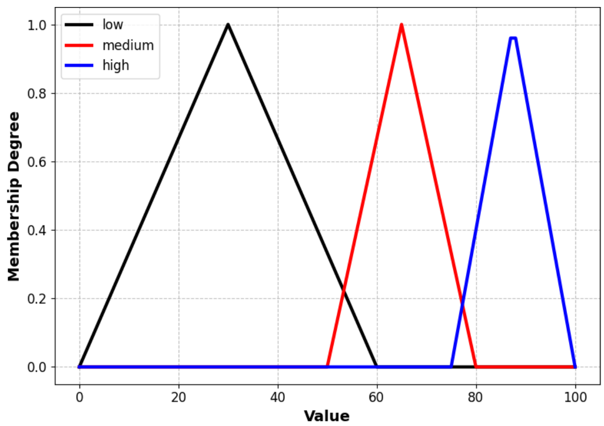

Fig. 4. Activation (membership) functions of the variable «Coating Uniformity»

5. Technology Compliance (0 or 1) characterizes whether the established requirements for correctly executing the anti-icing procedure are met.

Fuzzy sets: Not Complied (Regulations violated) → 0; complied (Regulations comply with) → 1.

Figure 5 shows the activation functions for a variable that determines its fuzzy sets and the degree to which each value belongs to the corresponding category.

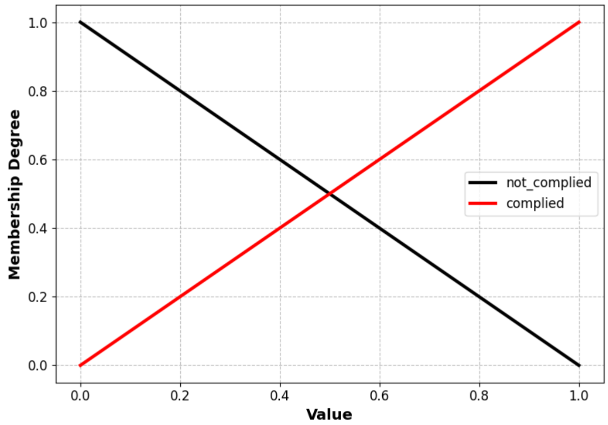

Fig. 5. Activation (membership) functions of the variable «Technology Compliance»

6. The ambient Temperature (°C) is a critical factor determining the rate of liquid drying and the risk of re-icing. Fuzzy sets: Low → (-10°C - 5°C); optimal → (4°C - 20°C); High → (15°C - 40°C).

Figure 6 shows the activation functions for a variable that defines its fuzzy sets and the degree of membership for each value in the corresponding category.

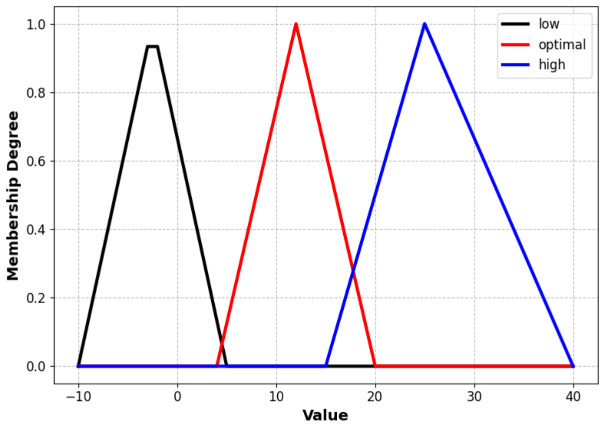

Fig. 6. Activation (membership) functions of the variable «Ambient Temperature»

7. The coverage (surface coverage, %) characterizes the surface part adequately treated with an anti-icing fluid.

Fuzzy sets: Poor (poor coverage) → (0–50%); Acceptable (Acceptable coverage) → (45–80%); Optimal (Optimal coverage) → (75–100%).

Figure 7 shows the activation functions for a variable that defines its fuzzy sets and the degree to which each value belongs to the corresponding category.

8. The drying Speed (coating drying and flow rate, min) characterizes the drying and flow rate of the coating. The faster the liquid dries, the less time it protects the surface from re-icing.

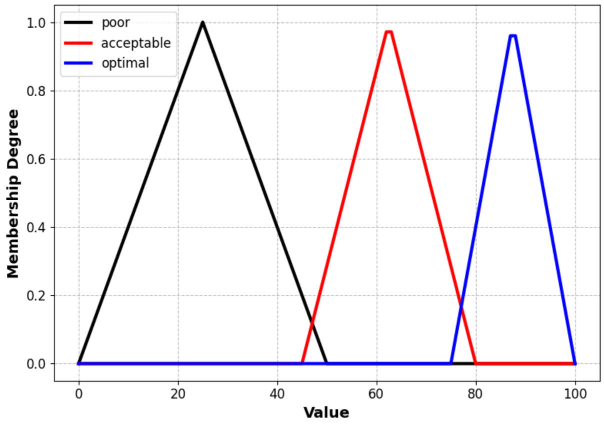

Fig. 7. Activation (membership) functions of the variable «Coverage»

Fuzzy sets: Fast (fast drying) → (0–10 min); optimal (optimal drying) → (8–20 min); slow (long drying) → (18–40 min).

Figure 8 shows the activation functions for a variable that determines its fuzzy sets and the degree to which each value belongs to the corresponding category.

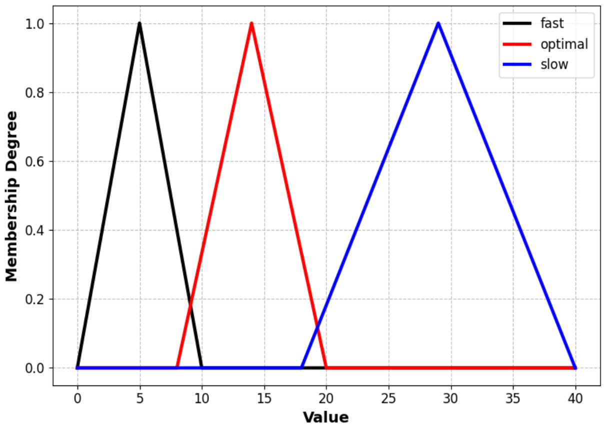

Fig. 8. Activation (membership) functions of the variable «Drying Speed»

9. Icing Type (type of icing) is a characteristic type that must be removed during the anti-icing procedure.

Fuzzy sets: Light Icing (light icing: ice crust, snow cover) → 1; Moderate Icing (moderate icing: icing due to frost fog) → 2; Severe Icing (severe icing: black ice, dense ice accumulation) → 3.

Figure 9 shows the activation functions for the variable, defining its fuzzy sets and the degree to which each value belongs to the corresponding category.

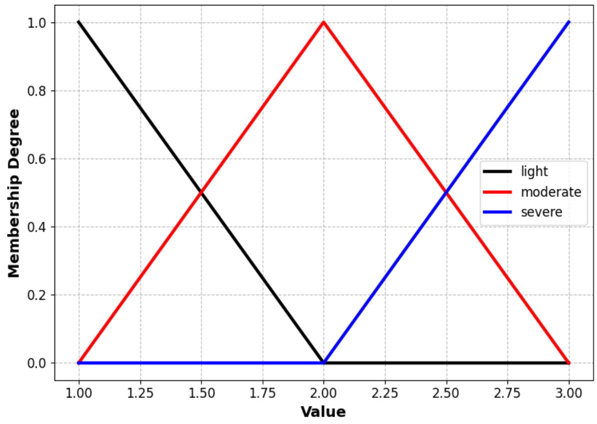

Fig. 9. Activation (membership) functions of the variable «Drying Speed»

Output Variable. Evaluation (Anti-icing Correctness Assessment, %) - evaluate the quality of anti-icing execution based on all input variables.

Fuzzy sets: Low (0 ... 40 %). Significant errors, technology violations, and ineffective coverage. Medium (41 ... 70 %). Partial procedure execution and the presence of minor errors. High (71 ... 100 %). Correct execution of all actions, optimal consumption, and uniform application.

Figure 10 shows the activation functions for a variable that determines its fuzzy sets and the degree to which each value belongs to the corresponding category.

Stage 3. Building a fuzzy logic rule base

To assess the correctness of anti-icing, a fuzzy rule base was built to model the interdependence between the input and output parameters to determine the correctness of the work performed on the aircraft anti-icing procedure.

The relationships between the variables and model rules are summarized in Table 1.

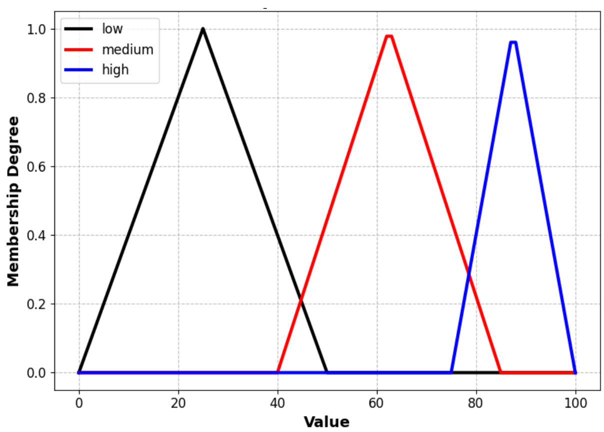

Fig. 10. Activation (membership) functions of the variable «Evaluation»

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Table 1

Base of model rules

№	Execution Time	Fluid Consumption	Coating Thickness	Uniformity	Regulation Compliance	Ambient Temperature	Coverage Level	Drying Speed	Icing Type	Evaluation Level
1	Fast	Low	Thin	Low	0	Low	Unsatisfactory	Fast	Light Icing	Low
2	Fast	Low	Thin	Low	0	Low	Unsatisfactory	Fast	Moderate Icing	Low
3	Fast	Low	Thin	Low	0	Low	Unsatisfactory	Fast	Severe Icing	Low
4	Fast	Low	Thin	Low	0	Low	Unsatisfactory	Optimal	Light Icing	Low
5	Fast	Low	Thin	Low	0	Low	Unsatisfactory	Optimal	Moderate Icing	Low
…	…	…	…	…	…	…	…	…	…	…
14154	Too Long	Low	Excessive	Low	0	High	Unsatisfactory	Optimal	Moderate Icing	Low
14155	Too Long	Low	Excessive	Low	0	High	Unsatisfactory	Optimal	Severe Icing	Low
14156	Too Long	Low	Excessive	Low	0	High	Unsatisfactory	Slow	Light Icing	Low
…	…	…	…	…	…	…	…	…	…	…
17497	Too Long	High	Excessive	High	1	High	Optimal	Slow	Severe Icing	Medium

Formally, this can be written as follows:

$$R_2\text{: IF}(\mu_{fast}(x_1) \wedge \mu_{low}(x_2) \wedge \mu_{thin}(x_3) \wedge \wedge \mu_{low}(x_4) \wedge \mu_{notComplied}(x_5) \wedge \wedge \mu_{low}(x_6) \wedge \mu_{unsatisfactory}(x_7) \wedge \wedge \mu_{fast}(x_8) \wedge \mu_{moderateIcing}(x_9) \quad (5)$$

$$\text{THEN } \mu_{low}(y), \quad (6)$$

where all variables are taken into account, and the minimum value of the membership functions determines the degree of activation of the rule:

$$\mu_{R2} = \min(\mu_{fast}(x_1),\ \mu_{low}(x_2),\ \mu_{thin}(x_3),\ \mu_{low}(x_4),\ \mu_{notComplied}(x_5),\ \mu_{low}(x_6),\ \mu_{unsatisfactory}(x_7),\ \mu_{fast}(x_8),\ \mu_{moderateIcing}(x_9)). \quad (7)$$

All rules in the system are defined similarly.

Stage 4. Rule aggregation and defuzzification

After determining the rules' activity, we obtain a fuzzy estimate that must be converted into a crisp value. The centre of gravity method was used to obtain the final results as follows:

$$y^* = \frac{\int y\mu(y)dy}{\int \mu(y)dy}, \quad (8)$$

where y* – final assessment of anti-icing performance; μ(y) – joint membership function of the output variable.

Considering all the activated fuzzy rules, the centre of gravity method allows us to obtain the most balanced assessment.

Stage 5. Software implementation of the model

To implement the assessment model, students’ acquired knowledge and skills in performing work on the anti-icing aircraft procedure and the scikit-fuzzy (skuzzy) library in the Python environment were used (Figure 11).

Visualization of the assessment results of the competencies acquired by the students in performing the anti-icing procedure allowed us to evaluate the zones of optimal parameters, identify risk areas and draw conclusions about the correctness of performing this procedure under various conditions. The contour graphs help determine the best combinations of input variables and identify the factors that have the most significant impact on the final result.

The graph in Figure 12 demonstrates how the anti-icing Execution Time and Fluid Consumption affect the procedure's efficiency.

Figure 13 shows how the anti-icing coating thickness and coverage level affect the accuracy of the anti-icing work. The best assessment was observed with a short execution time and low fluid consumption. With increased time and excess fluid consumption, the efficiency decreases, indicating the need for an optimal balance between the work speed and the rational use of the anti-icing fluid.

Having the opportunity to observe their changes (Fig. 13), we conclude that an excessively thick coating can reduce the effectiveness of anti-icing by prematurely flowing liquid or its uneven distribution. An optimal anti-icing zone with average thickness values and a high level of coating uniformity.

Low temperatures can slow drying down, which negatively affects the uniformity of the coating, and drying too fast can reduce the effectiveness of anti-icing protection. The optimum values were in the middle temperature range, with moderate drying and flow rates. The graph in Figure 15 characterizes the different icing types and Fluid Consumption.

```python
from google.colab import drive
import pandas as pd
import numpy as np
import skfuzzy as fuzz
import skfuzzy.control as ctrl
import matplotlib.pyplot as plt
drive.mount('/content/gdrive', force_remount=True)
file_path = '/content/gdrive/MyDrive/Colab Notebooks/data/anti_icing_fuzzy_rules.csv'
df_rules = pd.read_csv(file_path)
df_rules_limited = df_rules.head(100).copy()
...
...
for col, mapping in column_mappings.items():
    df_rules_limited.loc[:, col] = df_rules_limited[col].replace(mapping)
execution_time['fast'] = fuzz.trimf(execution_time.universe, [0, 2.5, 5])
execution_time['optimal'] = fuzz.trimf(execution_time.universe, [4, 7, 10])
execution_time['long'] = fuzz.trimf(execution_time.universe, [8, 11.5, 15])
execution_time['too_long'] = fuzz.trimf(execution_time.universe, [12, 16, 20])
fluid_consumption['low'] = fuzz.trimf(fluid_consumption.universe, [100, 200, 300])
fluid_consumption['optimal'] = fuzz.trimf(fluid_consumption.universe, [250, 475, 700])
fluid_consumption['high'] = fuzz.trimf(fluid_consumption.universe, [650, 825, 1000])
...
...
evaluation.defuzzify_method = 'centroid'
rules = []
for _, row in df_rules_limited.iterrows():
    compliance_value = "complied" if row["Regulation Compliance"] == 1 else "not_complied"
    rule = ctrl.Rule(
        execution_time[row["Execution Time"]] &
        fluid_consumption[row["Fluid Consumption"]] &
        coating_thickness[row["Coating Thickness"]] &
        coating_uniformity[row["Uniformity"]] &
        technology_compliance[compliance_value] &
        ambient_temp[row["Ambient Temperature"]] &
        coverage[row["Coverage Level"]] &
        drying_speed[row["Drying Speed"]] &
        icing_type[row["Icing Type"]],
        evaluation[row["Evaluation Level"]]
    )
    rules.append(rule)
if len(rules) == 0:
    raise ValueError(" Error: No rules loaded!")
print(f" Total rules loaded: {len(rules)}")
print("First 5 rules:", rules[:5])
evaluation_ctrl = ctrl.ControlSystem(rules)
evaluation_simulator = ctrl.ControlSystemSimulation(evaluation_ctrl)
def evaluate_anti_icing(test_case):
    keys = [
        'execution_time', 'fluid_consumption', 'coating_thickness',
        'coating_uniformity', 'technology_compliance', 'ambient_temp',
        'coverage', 'drying_speed', 'icing_type'
    ]
    for i, key in enumerate(keys):
        evaluation_simulator.input[key] = test_case[i]

    try:
        evaluation_simulator.compute()
        return evaluation_simulator.output['evaluation']
    except Exception as e:
        print(f" Calculation error: {e}")
        return None
test_case = (2, 150, 15, 20, 0, -5, 30, 5, 2)
result = evaluate_anti_icing(test_case)

if result is not None:
    print(f" Final anti-icing evaluation: {result:.2f}")
else:
    print(" Error in calculations")
```

```
Mounted at /content/gdrive
✅ Total rules loaded: 100
🔍 First 5 rules: [IF ((((((execution_time[fast] AND fluid_consumption[low]) AND coating_thickness[thin])
        AND aggregation function : fmin
        OR aggregation function  : fmax, IF ((((((execution_time[fast] AND fluid_consumption[low]) AND coa
        AND aggregation function : fmin
        OR aggregation function  : fmax, IF ((((((execution_time[fast] AND fluid_consumption[low]) AND coa
        AND aggregation function : fmin
        OR aggregation function  : fmax, IF ((((((execution_time[fast] AND fluid_consumption[low]) AND coa
        AND aggregation function : fmin
        OR aggregation function  : fmax, IF ((((((execution_time[fast] AND fluid_consumption[low]) AND coa
        AND aggregation function : fmin
        OR aggregation function  : fmax]
✅ Final anti-icing evaluation: 25.00
```

Fig. 11. A fragment of the software implementation of the fuzzy logic model in Python programming language

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

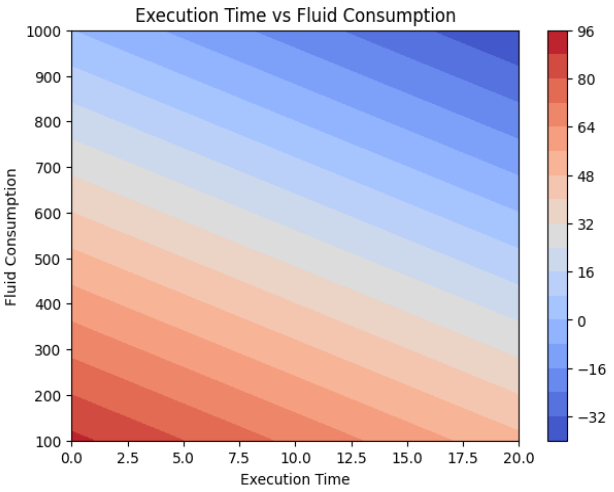

Fig. 12. Relationship between time and consumption of anti-icing fluid during anti-icing procedure

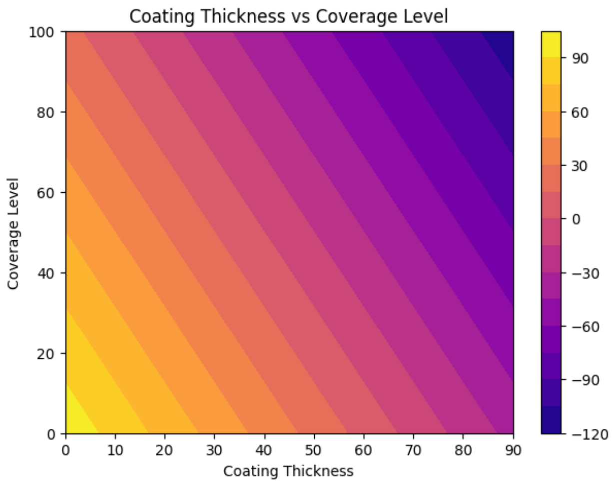

Fig. 13. Evaluation of the correctness of the anti-icing procedure based on the thickness of the anti-icing coating and its level of application

The influence of Ambient Temperature, Drying Speed, and liquid flow on the quality of the anti-icing procedure is shown in Figure 14.

Light icing (Icing Type = 1) requires minimal fluid consumption, and significantly heavier icing (Icing Type = 3). However, the graph also shows that substantially more fluid does not always yield the best result, again emphasizing the importance of optimal dosing of the fluid used for anti-icing.

The analysis of the relationship between the key parameters of anti-icing allowed us to identify the optimal zones for performing this procedure, and the contour graphs demonstrated that variable values that are too high or too low can negatively affect the effectiveness of anti-icing. Only the average values of the parameters yielded the best results.

Visualization of activation functions and contour graphs of the relationship between variables helped us understand the model's behaviour and solution. The centroid defuzzification method ensured a smooth transition between different levels of assessment of the competencies acquired by students in performing anti-icing work and their realism.

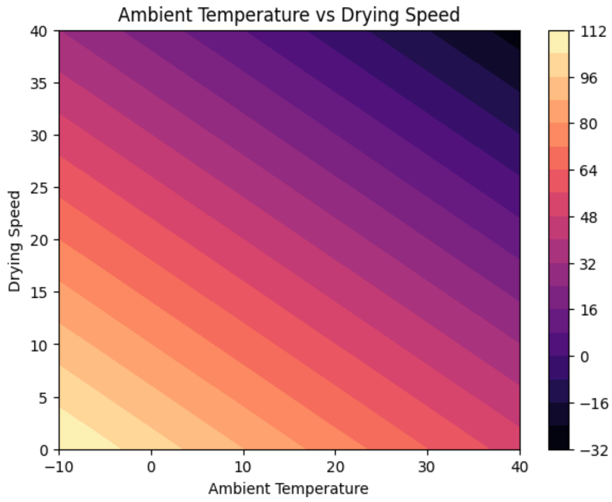

Fig. 14. Relationship between ambient temperature, drying rate, and flow rate of anti-icing coatings

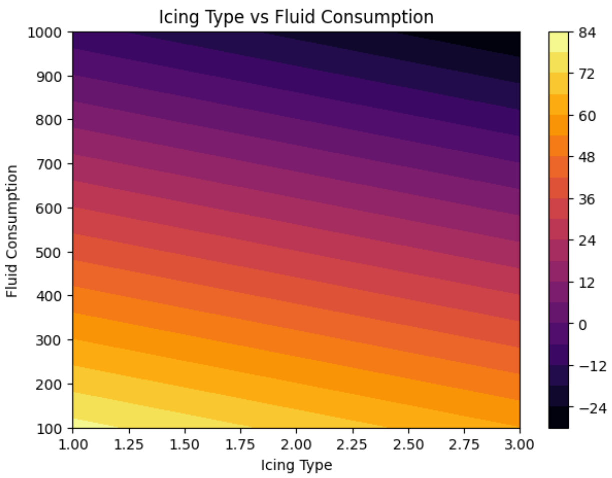

Fig. 15. Necessary consumption of anti-icing fluid depending on the type of freezing

Thus, the developed model should be recognized as an effective tool for assessing the correctness of aircraft anti-icing procedures, which is advisable both in the educational process for evaluating students' knowledge and in the corporate training of airline personnel.

4. Discussion

In the training and retraining of highly qualified specialists using gamification and AI technologies in the learning process, the issue of the realism of assessing their acquired competencies, which solution researchers propose using the fuzzy logic technique, is becoming increasingly acute. The fuzzy logic technique makes it possible to determine the level of specialist training, identify weaknesses in the educational process, and make timely adjustments to the training system. In particular, Sokol A. [36] used the fuzzy logic technique to determine the required level of knowledge, relying on the qualification characteristics of specialists, the number and complexity of tasks, the importance of acquiring practical skills, etc. The algorithm model proposed by the authors makes it possible to obtain an integrated assessment of the effectiveness of training specialists based on a combination of knowledge, real data on the duration of training, and statistical methods, thereby creating an adaptive automated knowledge control system. However, the proposed model is not sufficiently adapted for personnel with different levels of training and experience, which complicates both the training process and the assessment of the acquired knowledge and skills.

Kharchenko A. O. [37] developed a methodology for the expert assessment of the integrity of the preparation of qualification papers based on fuzzy logic and fuzzy systems of type-2. The authors proved that the fuzzy logic system of type-2 allows better modelling and management of the levels of uncertainty that occur in reality than when using the fuzzy logic system of type-1. Given the high computational complexity of developing fuzzy logical inference systems of type-2, it is advisable to use interval fuzzy sets of the second type. To determine the level of integrity, the researcher uses alpha levels, which allow for considering the incompleteness of data on existing influencing factors at each level of the hierarchical fuzzy logical inference system. This technique certainly deserves attention; however, it is fragmentary and should be recognized as a significant drawback.

Azimjonov J. [38] recommended a new methodology based on fuzzy logic for measuring student performance in distance learning institutions. The researchers initially divided the criteria for assessing student performance into primary and secondary categories. Four subparameters were classified as primary, and three subparameters were classified as secondary. The authors then scaled the sub-parameters to obtain accurate results. One disadvantage of the proposed methodology is the difficulty in interpreting and adjusting fuzzy parameters to assess student performance. In particular, because the system uses fuzzy sets and rules for assessment, changing the corresponding coefficients requires a large amount of data to accurately calibrate the model. This can lead to subjectivity when determining various performance criteria weights, making it difficult to obtain objective assessments.

Grzesik and Kowalik [39] applied a fuzzy logic approach to assess the acquired skills in anti-icing performance. The authors have described a fuzzy expert inference system that supports an algorithm for designing aircraft anti-icing systems. Serke, D. et al [40] proposed a radar icing algorithm (RadIA) that uses logic to determine the threat of weather radar detection. When analyzing the effectiveness of anti-icing procedures, this algorithm focuses on predicting possible icing, which is essential, but does not provide results for correctly determining the process.

The main idea of the author's model of assessment, acquired competencies by listeners, and correctness of their performance of the anti-icing procedure, is to create fuzzy variables, their pacification, and to build a base of fuzzy rules, which considers the interrelations between the process parameters. The model was constructed in several stages. First, nine input and one output variables (evaluation) are defined. Then, for each variable, fuzzy sets were created to determine the levels of characteristics and the corresponding triangular membership functions (trims), which were best suited for modelling the process. Then, the rules of fuzzy logic, formalizing the relationship between the input parameters and assessment, were implemented. In the calculation process, the T-norm (min) was used to determine the activity of the rules, and the centroid method was used to obtain the final assessment. The final implementation stage included the use of a fuzzy control system (Control System), which allowed the entry of new data, evaluation of results, and construction of graphs of membership functions.

Contour graphs were constructed to analyze the relationships between the key parameters of the correct execution of anti-icing works and demonstrate how changes in the input variables affect the final assessment of the quality of the procedure. The best assessment was obtained with a short execution time and a low level of liquid consumption. With increased time and excess liquid consumption, the efficiency decreases, indicating the need for an optimal balance between the work speed and the rational use of the anti-icing liquid. Visualization also confirmed the importance of temperature conditions, the correct choice of liquid consumption, optimal coating thickness, and duration of the anti-icing procedure.

The proposed model can be used for both educational and practical purposes. In particular, Aeroflot ground-handling personnel assess students' knowledge or training. This allows the simulation of various scenarios, based on which it is possible to analyze which factors impact the correctness of the anti-icing procedure. Owing to the phasing of parameters and fuzzy rules, the model provides flexibility in decision-making

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

and enables instructors or automated systems to generate recommendations to improve the performance of this procedure. In addition, the model can be adapted for use in digital twin systems for anti-icing processes, which will allow its integration into simulators or quality control systems for performing procedures during the ground handling of the air fleet.

5. Conclusions

The results of this study demonstrate that simulation, virtual reality, and artificial intelligence technologies have been actively integrated into the educational process of higher education institutions in recent years and have demonstrated the feasibility of their use. However, their use in the corporate training of aviation employees faces several problems. The first is the correctness of assessing competencies acquired by employees due to advanced training or retraining.

In search of solutions to solve a problem, an experiment was conducted to assess the competencies acquired by personnel performing anti-icing work on an aircraft. More than 350 people from among Kazakhstan's airline personnel participated in this experiment. Based on the experiment results, an original model was developed to assess the competencies acquired by the students and the accuracy of their performance in the anti-icing procedure. This involves creating fuzzy variables, phasing, and building a fuzzy rule base that considers the relationships among process parameters. The model was constructed in several stages. First, nine input and one output variable (Evaluation) were defined. Then, for each variable, fuzzy sets were created to determine the levels of characteristics and the corresponding triangular membership functions (trimf) best suited for modelling the process. Fuzzy logic rules were implemented to formalize the relationship between the input parameters and evaluation. The calculation process used the T-norm (min) to determine the activity of the rules and the centroid method to obtain the final assessment. The final stage of the implementation included the use of a fuzzy control system (Control System), which allowed the entry of new data, evaluation of the results, and plotting membership functions.

Thus, based on the results of the experiment, the feasibility of using immersion technologies based on the synergy of gamification and artificial intelligence in corporate training of civil aviation employees was proven, which will ensure the interactivity of the educational process, its constructivism and implementation according to a practice-oriented approach, as well as carry out a more realistic assessment of the competencies acquired by the personnel for their subsequent certification following international standards.

Further research will be conducted to develop a methodology for assessing the correctness of group task performance by the team as a whole and by each team member individually. For this purpose, under the Project under the grant of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan No. AP19680080 ‘Development of a training complex with a system of engineering support for the technical operation of military and special aviation transport equipment’, several experiments will be conducted among the civil aviation personnel of the Republic of Kazakhstan.

Contribution of authors: conceptualization, methodology – **Kayrat Koshekov, Rustam Togambayev**; formulation of tasks, analysis – **Nataliia Levchenko**; development of model, software, verification – **Kayrat Koshekov, Abay Koshekov, Ildar Pirmanov**; analysis of results **- Natalia Levchenko**, visualization – **Abay Koshekov, Yuri Tanovitsky, Yakub Kurbanov**; writing – original draft preparation – **Kayrat Koshekov**, **Rustem Togambayev**; writing – review and editing – **Kayrat Koshekov**, **Abay Koshekov.**

Project information: Project under the grant of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan No. AP19680080 «Development of a training complex with a system of engineering support for the technical operation of military and special aviation transport equipment».

The overwhelming number of training stands for aviation devices, systems, and units currently used in the Republic of Kazakhstan, as well as the aviation equipment to which they relate, are outdated. Ordering training stands that meet modern requirements costs as much as a real aircraft unit, instrument, or system. The use of three-dimensional models and virtual reality technologies will make it possible to create virtual training benches that meet modern requirements for training aviation technical personnel and to multiply them with minimal costs only for virtual reality equipment.

According to the conducted analyses, the most appropriate software life cycle model was chosen – an iterative incremental model of creating a training application for students of full-time, part-time and distance education on the aviation module ‘Aerodynamics, Design and Systems’. This model is considered the fundamental basis of modern software development approaches. The model is characterized by a certain duality:

- From the point of view of the application life cycle, this model is considered iterative because it implies repeated repetition of the same stages;
- From the point of view of application development (adding useful functionality to it), the model is

considered incremental.

The relevance and importance of the proposed scientific solutions provides a significant economic effect because it is 100% safe for students, replaces training in practice, no airport pass is required, no risk of possible damage to the aircraft or injuries during training, organization of practices with an unlimited number and without large costs, taking into account expensive resources and time, the possibility of stopping the simulation to discuss the problem with the trainee, simulation of any weather conditions and surface conditions, simulation of risky situations. In the conditions of online learning implementation, the organization of virtual internships, practical and laboratory classes to ensure practical competences of future specialists becomes a significant project.

Due to the importance of the project for the aviation of Kazakhstan, the project aimed to develop, test and implement the technology of designing digital simulators with engineering support system for the technical operation of military and special aviation transport equipment on the basis of 3D-modelling and virtual reality to ensure high-quality theoretical and practical training following the requirements of international standards and recommended practices of ICAO, EASA and IATA.

A number of scientific and practical tasks have been solved to achieve the set goal. Firstly, design technologies based on methods and algorithms for transforming design documentation into the likeness of real objects were developed. Databases of 3d models of the photorealistic quality of instrument panels and control elements of military and special aviation transport equipment, as well as their textures for further use, have been created. Structuring and storage of files according to the criteria of optimizing the speed of access to information for further design of digital simulators. **Kayrat KOSHEKOV, Abay KOSHEKOV** and **Yuri TANOVITSKIY** are the executors of this project.

Second, a hardware-software complex of implementation of digital simulators for maintenance and operation of military and special aviation transport equipment was designed: an anti-blanketing machine, slurry machine, ambulatory lift, autotrap, container transloader, belt transloader, baggage tractor, driver tractor, driverless tractor, and armoured vehicles. The executors of this project are **Rustam TOGAMBAYEV, Abay KOSHEKOV and Yuri TANOVITSKIY**.

Third, a simulator complex with an engineering support system for the technical operation of military and special aircraft transport equipment was developed. Creation of client-server logic of the application, allowing control of several connected clients from one server. **Rustam TOGAMBAYEV, Ildar PIRMANOV** and **Nataliia LEVCHENKO** are the executors in this area.

Fourth, a Commercialization Centre was established by organizing training and issuing certificates and a licence to operate special equipment at the aerodrome in accordance with the requirements of international standards and recommended practices of ICAO, EASA and IATA. **Kayrat KOSHEKOV, Nataliia LEVCHENKO** and **Abay KOSHEKOV** were involved in the development of technical documentation and organisational issues related to the opening of the Centre.

Fifth, an important element of the project is the development of an intelligent system to assess trainees' practical competences. The results of research in this direction are presented in this article. The executors are **Rustam TOGAMBAYEV, Kayrat KOSHEKOV, Nataliia LEVCHENKO** and **Abay KOSHEKOV.**

Approbation of the results of experimental research on the project in the conditions of JSC 'Almaty International Airport' allows us to assert that the following problematic issues of the organization of educational and production processes are successfully solved: high level of correspondence of real objects and processes in virtual training, simultaneous multi-user scenarios for coordinated training of the team, individual responsibility for the actions performed in the process of training, reducing the influence of the human factor on the training process. A standard for training personnel in the air transport industry and an innovative approach to training based on interactive training methods are being developed.

Based on advanced information and communication technologies, the authors of the project have developed and implemented at JSC 'Aircraft Repair Plant No. 405' a management system, which allows, thanks to the developed simulators, not only to create interactive scenarios based on virtual reality technologies to ensure deep immersion in the studied material but also to conduct the educational process with full administration and data analysis. The software is implemented on the Moodle platform, which provides a high level of security and flexibility to customize the process of publishing training materials and the process of studying materials based on the time spent studying the material to fix practically correct and incorrect actions. Also advantageous is the ability to integrate popular services: Zoom, Google Meet, Big Blue Button, and Google Calendar. **Ildar PIRMANOV** and **Yakub KURBANOV** developed the structure and model of the management system and software of the educational platform

In addition, as a result of the project implementation, a new concept of methodological support for the maintenance and operation of military and special aviation transport equipment with modelling of standard and abnormal situations during operation for practical training was proposed. The material for each type of equip-

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

ment includes 4 types of content: lectures with textual content, video materials, test control tasks, and practical exercises using simulators. Approbation of the methodological support and software of the educational process management system in the conditions of JSC ‘Aircraft Repair Plant No. 405’ showed many advantages for application: high speed of loading of educational material when using the web version is much higher, guaranteed correct display of content, fast and unlimited creation of copies of materials in the conditions of complex production process. **Rustam TOGAMBAYEV, Ildar PIRMANOV, Nataliia LEVCHENKO** and **Yakub KURBANOV** were engaged in experimental research and development of the concept and implementation of methodological support

The project is significant at the international level in the field of modernization of education and development of information and telecommunication technologies, aircraft engineering, intellectual technologies, digital signal and image processing.

The implementation of this project contributes to the development of innovative directions in aviation science, such as the application of artificial intelligence in knowledge assessment and the use of technical vision, machine learning, Deep Learning, Data Science and Big Data.

Conflict of Interest

The authors declare that they have no conflict of interest related to this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19680080). «Development of training complex with a system of engineering support for the technical operation of military and special aviation transport equipment».

Data Availability

The code for launching the developed diagnostic monitoring system is available at the link https://colab.research.google.com/drive/1NFBPytQjGwpB8abd8nlCzcy9NDkPxEsy?usp=sharing

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All the authors have read and agreed to the published version of this manuscript.

References

1. Kozub, G., Shinkarenko, Ya., & Kozub, V. Heymifikatsiya v osviti: intehratsiya Classcraft v navchalnyi protses [Gamification in education: integrating Classcraft into the learning process]. *Pedahohichna Akademiya: naukovi zapysky - Pedagogical Academy: Scientific Notes*, 2024, vol. 7, pp. 1-20. DOI: 10.57125/pedacademy.2024.06.29.02. (In Ukrainian).

2. Makhanov, K. *Aviation in Kazakhstan: An Economic View*. Available at: https://www.eurasian-research.org/publication/aviation-in-kazakhstan-an-economic-view/ (accessed 08.04.2025).

3. *Final Meeting on the Results of Passenger Service, Baggage and Cargo Handling in 2024 and plans for 2025*. Available at: https://caa.gov.kz/en/blog/post/final-meeting-results-passenger-service-baggage-and-cargo-handling-2024-and-plans-2025 (accessed 08.04.2025).

4. *Transport statistics*. Available at: https://stat.gov.kz/industries/business-statistics/stat-transport/ (accessed 09.04.2025) (In Kazakh).

5. Koshekov, K., Togambayev, R., Toiganbayev, B., Kenbeilova, S., Koshekov, A., & Pirmanov, I. Development of a neural network approach for risk management in helicopter technical condition diagnostics. *Eastern-European Journal of Enterprise Technologies*, 2024, vol. 6, no. 3(132), pp. 25-36. DOI: 10.15587/1729-4061.2024.312345.

6. *Aviatsiyany damıtu: Qazaqstanda jana auejaylar salynyp, aue qatınasy keneytilude* [Aviation development: Kazakhstan builds new airports and expands air traffic]. Available at: https://ortcom.kz/kk/deyatelnost-pravitelstva/1739943281 (accessed 08.04.2025). (In Kazakh).

7. Koshekov, K., Seidakhmetov, B., Savostin, A., Anayatova, R., & Fedorov, I. Aviation Profiling Method Based on Deep Learning Technology for Emotion Recognition by Speech Signal. *Transport and Telecommunication Journal*, 2021, vol. 22, no. 4, pp. 471–481. DOI: 10.2478/ttj-2021-0037.

8. Koshekov, K., Pirmanov, I., Alibekkyzy, K., Belginova, S., Karymsakova, M., & Baidildina, A. Digital twins technology in the educational process of the aviation equipment repair. *Indonesian Journal of Electrical Engineering and Computer Science*, 2023, vol. 32, no. 2, pp. 752-762. DOI: 10.11591/ijeecs.v32.i2.pp752-762.

9. Nadirova, G. *The Transformative Impact of AI on Education: Challenges and Opportunities*. Available at: https://www.eurasian-research.org/publication/the-transformative-impact-of-ai-on-education-challenges-and-opportunities/ (accessed 08.04.2025).

10. Ainakulov, Z., Astapenko, N., Pirmanov, I., Kurmankulova, G., Fedorov, I., Koshekov, K., & Zuev,

D. Risk Assessment of the Operation of Aviation Maintenance Personnel Trained on Virtual Reality Simulators. *Transport and Telecommunication Journal*, 2022, vol. 23, no. 4, pp. 320–333. DOI: 10.2478/ttj-2022-0026.

11. Capatina, A., Juarez-Varon, D., Micu, A., & Micu, A. E. Leveling up in corporate training: Unveiling the power of gamification to enhance knowledge retention, knowledge sharing, and job performance. *Journal of Innovation & Knowledge*, 2024, vol. 9, no. 3, art. no. 100530. DOI: 10.1016/j.jik.2024.100530.

12. Chiu, T.K.F., Lin, T.-J., & Lonka K. Motivating Online Learning: The Challenges of COVID-19 and Beyond. *The Asia-Pacific Education Researcher*, 2021, vol. 30, pp. 187-190. DOI: 10.1007/s40299-021-00566-w.

13. Nieto-Escamez, F., & Roldan-Tapia M. Gamification as Online Teaching Strategy During COVID-19: A Mini-Review. *Frontiers in Psychology*, 2021, vol. 12, art. no. 648552. DOI: 10.3389/fpsyg.2021.648552.

14. Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. Integrating Augmented Reality, Gamification, and Serious Games in Computer Science Education. *Education Sciences*, 2023, vol. 13, no. 6, art. no. 618. DOI: 10.3390/educsci13060618.

15. Marshall, D. T., Love, S. M., & Shannon, D. M. How teachers experienced the COVID-19 transition to remote instruction. *Phi Delta Kappan*, 2020, vol. 102, no. 3, pp. 46-50. DOI: 10.1177/0031721720970702.

16. Ferri, F., Grifoni, P., & Guzzo, T. Online Learning and Emergency Remote Teaching: Opportunities and Challenges in Emergency Situations. *Societies*, 2020, vol. 10, no. 4, art. no. 86. DOI: 10.3390/soc10040086.

17. Lampropoulos, G. Educational benefits of digital game-based learning: K-12 teachers' perspectives and attitudes. *Advances in Mobile Learning Educational Research*, 2023, vol. 3, no. 3, pp. 805-817. DOI: 10.25082/AMLER.2023.02.008.

18. Arufe Giráldez, V., Sanmiguel-Rodríguez, A., Ramos Álvarez, O., & Navarro-Patón, R. Can Gamification Influence the Academic Performance of Students? *Sustainability*, 2022, vol. 14, no. 9, art. no. 5115. DOI: 10.3390/su14095115.

19. Yıldırım, I., & Şen, S. The effects of gamification on students' academic achievement: a meta-analysis study. *Interactive Learning Environments*, 2019, vol. 29, no. 8, pp. 1301–1318. DOI: 10.1080/10494820.2019.1636089.

20. Poluru, N. Enhancing Student Authenticity and Engagement Through Gamification and Problem-Based Learning in Higher Education. *Enhancing Engagement With Gamification: Education, Business, and Healthcare Perspectives*, 2025, pp.29-52. DOI: 10.4018/979-8-3693-8322-3.ch002.

21. Kim, J., & Castelli, D. M. Effects of Gamification on Behavioral Change in Education: A Meta-Analysis. *International Journal of Environmental Research and Public Health*, 2021, vol. 18, no. 7, art. no. 3550. DOI: 10.3390/ijerph18073550.

22. Pozo-Sánchez, S., Lampropoulos, G., & López-Belmonte, J. Comparing Gamification Models in Higher Education Using Face-to-Face and Virtual Escape Rooms. *Journal of New Approaches in Educational Research*, 2022, vol. 11, no. 2, pp. 307-322. DOI: 10.7821/naer.2022.7.1025.

23. Kaufmann, D. Reflection: benefits of gamification in online higher education. *Journal of Instructional Research*, 2018, vol. 7, no.1, pp. 125-132. DOI: 10.9743/jir.2018.12.

24. Marín, B., Frez, J., Cruz-Lemus, J., & Genero, M. An Empirical Investigation on the Benefits of Gamification in Programming Courses. ACM Transactions on Computing Education. *IGI Global*, 2018, vol. 19, no. 1, pp. 1-22. DOI: 10.1145/3231709.

25. Moshkova, N., Alieksieieva, H., Horbatiuk, L., Kravchenko, N., & Cortez, J.I. Heimifikatsiya yak odyn iz trendiv suchasnoyi osvity [Gamification as one of the trends in modern education]. *Youth & market*, 2024, vol. 4, no. 224, pp. 82-87. DOI: 10.24919/2308-4634.2024.300147. (In Ukrainian).

26. Baumuratova, D., Zhukabayeva, T., & Rakhim zhanova, M. Gamification as a Tool for Personalized Learning in Inclusive Education. *Proceedings of the 9th International Conference on Computer Science and Engineering*, Antalya, Turkey, IEEE, 2024, pp. 1024-1029. DOI: 10.1109/UBMK63289.2024.10773443.

27. Kapp, K.M. Choose Your Level: Using Games and Gamification to Create Personalized Instruction. *Handbook on personalized learning for states, districts, and schools*, 2016, pp. 131-143. Available at: https://youre.vn/wp-content/uploads/2021/09/Handbook-on-Personalized-Learning.pdf#page=147 (accessed 09.04.2025).

28. Velazquez-Garcia, L., Cedillo-Hernandez, A., Longar-Blanco, M. D. P., & Bustos-Farias, E. Enhancing Educational Gamification through AI in Higher Education. *IGI Global*, 2024, pp. 213-218. DOI: 10.1145/3702163.3702416.

29. Thai, N. T. T., De Wever, B., & Valcke, M. Face- to- face, blended, flipped, or online learning environment? Impact on learning performance and student cognitions. *Journal of Computer Assisted Learning*, 2020, vol. 36, no. 3, pp. 397-411. DOI: 10.1111/jcal.12423.

30. Bresciani, S., Huarng, K.-H., Malhotra, A., & Ferraris, A. Digital transformation as a springboard for product, process and business model innovation. *Journal of Business Research*, 2021, vol. 128, pp. 204–210. DOI: 10.1016/j.jbusres.2021.02.003.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

31. Bayraktarlı, Ö. F., & Selçuk, S. A. Gamification as a Pedagogical Innovation in Architectural Education, 2024, pp. 69-102. DOI: 10.4018/979-8-3693-8322-3.ch004.

32. Kraus, S., Ferraris, A., & Bertello, A. The future of work: How innovation and digitalization reshape the workplace. *Journal of Innovation & Knowledge*, 2023, vol. 8, no. 4, art. no. 100438. DOI: 10.1016/j.jik.2023.100438.

33. Badea, G., & Popescu, E. Integrating a Comprehensive Gamification Model in a Peer Assessment Platform. *Proceedings of the 28th International Conference on System Theory, Control and Computing*, Sinaia, Romania, IEEE, 2024, pp. 385-390. DOI: 10.1109/ICSTCC62912.2024.10744765.

34. Srimathi, S., & Anitha, D. A Multi Criteria Decision Making approach to integrate Gamification in Education. *Journal of Engineering Education Transformations*, 2024, vol. 37, pp. 262–270. DOI: 10.16920/jeet/2024/v37is2/24049.

35. Minoretti, P., & Emanuele, E. Health in the Skies: A Narrative Review of the Issues Faced by Commercial Airline Pilots. *Cureus*, 2023, vol. 15, no. 4, art. no. 38000. DOI: 10.7759/cureus.38000.

36. Sokol, A. Metod otsinyuvannya rezultativ diyal'nosti sudnovodiiv pid chas trenazhernoi pidgotovky [Risk assessment analysis for the operation of rovs in servicing offshore extraction complexes]. *Water transport*, 2024, vol. 3, no. 41, pp. 23-32. DOI: 10.33298/2226-8553.2024.3.41.03. (In Ukrainian).

37. Kharchenko, A. Ekspetne otsinyuvannya akademichnoi dobrochesnosti v zakladah vyshchoyi osvity za dopomogoyu nechitkoyi logiky [Expert assessment of academic integrity in higher education institutions using fuzzy logic]. *Scientific notes of young scientists*, 2023, vol. 12, pp. 1-8. Available at: https://phm.cuspu.edu.ua/ojs/index.php/SNYS/article/view/2071. (accessed 09.04.2025) (In Ukrainian).

38. Azimjanov, J., Hakan Selvi, I., & Ozbek, U. Evaluation of distance learning students' performance using fuzzy logic. *Journal of Management Information Systems*, 2016, vol. 1, no. 3, pp. 87-97. Available at: https://scispace.com/pdf/evaluation-of-distance-learning-students-performance-using-3a9xo2oxn2.pdf (accessed 09.04.2025).

39. Grzesik, N., & Kowalik, K. Fuzzy Controller for Aircraft Anti-Icing System - Initial Design and Analysis. *Solid State Phenomena*, 2016, vol. 251, pp. 218-223. DOI: 10.4028/www.scientific.net/ssp.251.218.

40. Serke, D. J., Albo, D. E., Ellis, S. M., Haggerty, J. A., Hubbert, J. C., & Tessendorf, S. A. Radar Icing Algorithm: Algorithm Description and Comparison with Aircraft Observations. *Journal of Atmospheric and Oceanic Technology*, 2022, vol. 39, no. 1, pp. 91-109. DOI: 10.1175/jtech-d-21-0003.1.

Received 17.03.2025, Accepted 20.05.2025

ЦИФРОВІЗАЦІЯ ОСВІТНЬОГО ПРОЦЕСУ: СИНЕРГІЯ ГЕЙМІФІКАЦІЇ ТА ШТУЧНОГО ІНТЕЛЕКТУ ПРИ ПІДГОТОВЦІ ВИСОКОКВАЛІФІКОВАННИХ СПЕЦІАЛІСТІВ ЦИВІЛЬНОЇ АВІАЦІЇ

Р. К. Тогамбаєв, І. А. Пірманов, К. Т. Кошеков, Н. М. Левченко, А. К. Кошеков, Ю. М. Тановицький, Я. М. Курбанов

Предметом дослідження є процес цифрової трансформації освітнього процесу підготовки висококваліфікованих спеціалістів повітряного транспорту, а також перепідготовки та підвищення кваліфікації працівників цивільної авіації з метою набуття ними необхідних компетентностей для забезпечення безпеки польотів. Підкреслено, що технології симуляції, віртуальної реальності та штучного інтелекту останніми роками досить активно інтегрувалися в освітній процес вищих навчальних закладів і довели доцільність їх застосування. Однак, їх застосування при корпоративному навчанні співробітників авіації ускладнюється цілою низкою перепон. Серед яких передусім слід звернути увагу на правильність оцінювання набутих співробітниками компетенцій, що є вкрай необхідним під час ухвалення рішень щодо сертифікації набутих ними компетентностей. **Ціль -** обґрунтувати, спираючись на результати експерименту, доцільність застосування під час корпоративного навчання працівників цивільної авіації імерсійних технологій, які ґрунтуються на синергії гейміфікації та штучного інтелекту, що надасть змогу забезпечити інтерактивність освітнього процесу, його конструктивізм та реалізацію за практико-орієнтованим підходом, а також здійснити більш реалістичне оцінювання набутих персоналом знань та навиків задля сертифікації рівня їх компетентностей у відповідності до вимог міжнародних стандартів. **Результати**. Керуючись вимогами міжнародних стандартів, зокрема щодо виконання робіт з анти-айсингу літаків, розроблено модель оцінювання набутих співробітниками за результатами проходження корпоративного навчання компетентностей в частині правильності виконання анти-айсингу літаків. Дана модель оцінки набутих компетентностей заснована на нечіткій логіці, що дає змогу опрацьовувати параметри з нечіткими межами і реально оцінити якість виконання процедури анти-айсингу. Методологія її побудови базується на нечіткій фазифікації вхідних змінних, побудові бази правил і дефазифікації для отримання підсумкової оцінки. **Висновки**. За результатами дослідження доведено доцільність застосування імерсійних технологій під час корпоративного навчання співробітників цивільної авіації, а також розроблено модель оцінювання набутих ними компетенцій, застосування якої на практиці надасть змогу реально оцінювати набуті знання та навички працівників авіакомпаній та сертифікувати рівень їх компетентностей відповідно до міжнародних стандартів.

Ключові слова: цифрова трансформація освітнього процесу; імерсійні технології навчання; гейміфікація; гейміфіковане навчання; штучний інтелект.

Тогамбаєв Рустам Кумарбекович – маг., асп. Телематика і логістика, Інституту транспорту та зв'язку, Рига, Латвія.

Пірманов Ільдар Ануарбекович - маг., асп. каф. авіаційної техніки і технологій Академії цивільної авіації, Алмати, Республіка Казахстан.

Кошеков Кайрат Темірбаєвич - д-р техн. наук, проф., головний науковий співробітник Інституту механіки і машинознавства ім. У.А. Джолдасбекова, Алмати, Республіка Казахстан, проф. каф. авіаційної техніки і технологій Академії цивільної авіації, Алмати, Республіка Казахстан.

Левченко Наталія Михайлівна – д-р держ. упр., проф. Інституту соціології Технічного університету Берлін, Німеччина.

Кошеков Абай Кайратович – PhD, асоц. проф. каф. авіаційної техніки і технологій Академії цивільної авіації, Алмати, Республіка Казахстан.

Тановицький Юрій Миколайович – канд. техн. наук, наук. співроб. Центру наукових досліджень та компетенцій Академії цивільної авіації, Алмати, Республіка Казахстан.

Курбанов Якуб Мухсатұлы – маг., керівник Центру наукових досліджень та компетенцій Академії цивільної авіації, Алмати, Республіка Казахстан.

Rustam Togambayev – Master, PhD Student of the Telematics, Transport and Telecommunication Institute, Riga, Latvia,
e-mail: r.togambayev@tsi.lv, ORCID: 0000-0002-0045-5764. Scopus Author ID: 59521322800.

Ildar Pirmanov – Master, PhD Student, Department of Aviation Technique and Technologies, Civil Aviation Academy, Almaty, Republic of Kazakhstan,
e-mail: i.pirmanov@agakaz.kz, ORCID: 0000-0002-6028-0812. Scopus Author ID: 57483954800.

Kayrat Koshekov – Doctor of Technical Sciences, Professor, Department of Aviation Technique and Technologies, Civil Aviation Academy, Almaty, Republic of Kazakhstan,
e-mail: k.koshekov@agakaz.kz, ORCID: 0000-0002-9586-2310, Scopus Author ID: 56150300500.

Nataliia Levchenko – Doctor of Science in Public Administration, Professor at the Institute of Sociology in the Technical University of Berlin, Germany,
e-mail: levchenkon65@gmail.com, ORCID: 0000-0002-3283-6924, Scopus Author ID: 57258686100.

Abay Koshekov – PhD, Associate Professor, Department of Aviation Technique and Technologies, Civil Aviation Academy, Almaty, Republic of Kazakhstan,
e-mail: a.k.koshekov@gmail.com, ORCID: 0000-0001-7373-1494, Scopus Author ID: 57192438940.

Yuri Tanovitskiy – Candidate of Technical Sciences, Researcher of the Centre for Scientific Achievements, Civil Aviation Academy, Almaty, Republic of Kazakhstan,
e-mail: y.tanovitskiy@agakaz.kz, ORCID: 0009-0001-5217-1245, Scopus Author ID: 54400321400.

Yakub Kurbanov – Master, Head of the Centre for Scientific Achievements, Civil Aviation Academy, Almaty, Republic of Kazakhstan,
e-mail: y.kurbanov@agakaz.kz, ORCID: 0000-0002-8883-600X.