Digital twins technology in the educational process of the aviation equipment repair

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ABSTRACT

The article considers the digital transformation of the aviation industry based on twins of maintenance and repair. As a result of digitization, a set of documents and application software are formed in a virtual reality environment. The concept of a digital twin is presented in the context of a model-based system design of the helicopter maintenance process according to the technical regulations. Based on statistical modeling technologies, a model for assembling aircraft units has been developed, in which time characteristics are qualitative estimates of learning processes and the effectiveness of digital twins. The results of experimental studies based on the method of analysis of students' certification using digital twins in the assembly of aircraft units are presented. It has been established that at the production site of an aircraft repair enterprise it is effective to apply training at the first stage using digital twins, and at the second stage using real objects. Based on analytical and experimental studies, regression models are proposed for the relationship between the optimal number of trainings at the second stage and the relative coefficient of training time for successful training and certification of mechanics and electronics engineers.

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1. INTRODUCTION

An analysis of materials in the field of digital transformation and technologies in the format of digital twins, published in scientific articles and production plans, showed that at present, clear reasonable standards have not yet been formed in this scientific and practical environment. The history of the discussion of this topic is rooted in ancient Greek philosophy. According to the authors, this problem should be approached from a systematic methodological standpoint. Where, there are many questions and uncertainties, and it is necessary to start in any new work with the formulation and justification of the goal. Target selection should be considered a major issue especially in the initial phase of any new research or project. The choice of the goal is made correctly and quite often the goal is replaced by a task; the functions of the system are mistakenly replaced by means of achieving the goal. The problematic nature and key importance of this systemic project stage is considered in detail in the work of Nadler and Hibino [1]–[3].

The main practical questions that arise in the study of digital twins are: where does organoleptic sensation end and virtual simulated images begin? In any study cited in the open press, the quantitative assessment of the quality of an object or process is based on empirical results. In each study, the requirement to achieve the goal is declared, or it is argued that the goal has already been achieved, and it has been achieved "exactly". At the same time, in the conditions of parametric fuzziness and uncertainty of data, which are encountered in every project or study without exception, a detailed study of the entire trajectory of the formation of the final uncertainty of the result obtained is not provided, which would be the final systemic assessment of accuracy. In any management process there is a control stage, which consists of: measuring, comparing the measured value with the standard and making a decision. In this chain of management acts, there is a concept: a standard (tolerance, limit).

The standard is an integral and dominant component in digital twin technologies. At the same time, in most known and proposed approaches and models in this subject area, the standard is considered a deterministic value, which significantly distorts the modeling result. The identified problems pose tasks that are considered to a certain extent in the proposed article. The scientific and practical tasks in the proposed article are solved by the example of maintenance and repair of aviation equipment. The most significant theoretical and practical results have appeared in this industry, as well as the problems that have arisen.

2. LITERATURE REVIEW

In it is noted that in aviation, at all stages of the life cycle of this product, traditional approaches in design, production and operation technologies show their extreme inefficiency in practice. Here there is a "need for a fundamental shift" in this system and the birth of a new "paradigm". This paradigm is a "digital twin", which is integrated into the on-board control system of the technical condition of the aircraft on the basis of "ultra-high precision modeling" [4]. Using the available historical data of the operation system, they will provide an unprecedented level of safety and reliability of flights.

A similar concept, in which software models simulate reality based on information coming from the physical world, was proposed by David Gelernter in 1991 and was called "Mirror Worlds" [5]. These approaches, expressed as a new concept of digital twins, were first proposed by M. Greaves in 2002 at the University of Michigan [6]. The conceptual model proposed by the author contains three agents: a real space agent, a virtual space agent, and an information agent. All three agent models are aggregated programmatically into a single system, where the subject of control is assigned a certain role.

By 2006, the name of Greaves' conceptual model had been changed to "information mirroring model". In such a transformation, the mechanism of communication between the two spaces, virtual and real, with feedback between them is emphasized. The possibility of multiple virtual spaces for one real space is assumed. As practice shows, the introduction of digital twins will grow exponentially. This phenomenon leads to terminological confusion. In the works [7], [8] it is also indicated that it has long been necessary to develop some standards that should more accurately define the basic concepts in the new technology–the digital twin. This standard introduces a single definition of the digital twin, and its digital transformation is considered as a system.

In the aviation industry, the process of digital transformation is considered differentiated by individual phases of the aircraft life cycle. During the maintenance and repair phase of the aircraft, the digital transformation was carried out in two stages. At the first stage, the operational documentation of aircraft and UAVs is digitized. This digital document and accompanying software are called an interactive electronic technical manual, which is used in the inspection and repair of aircraft. This software package is known as the technical guide builder (TGB) [9], [10]. Already at this stage of digitalization, there is a reduction in aircraft maintenance time, since detailed technological information about the design parameters of each element is "embedded" into the software. This digital complex is called a digital layout. The digital twin is the next step in the digital transformation of this layout. To do this, even at the plant, all important systems, units and components of the aircraft are equipped with special sensors. Information during the flight from each sensor is recorded in real time on special media in the onboard computer system. After the aircraft (helicopter) has landed, this information is read by a special "intellectual machine" in which technical diagnostics of all information takes place.

The most important characteristic of digital twins is the metrological indicators of accuracy, reliability of the processes of diagnosing the technical condition of the control object and the risks of control as a system as a whole [11], [12]. In this publication, accuracy refers to a 3D model and the data with which this three-dimensional form is "filled". The sources of information about the technical condition are sensors, which, as it appears in the article, are connected by specialists. It should be noted that the sensors cannot be "connected by specialists" during the operation of complex aircraft units, since this must be decided at the stage of design development and manufacture of the unit. It should be noted that the accuracy and risk requirements of the control system are not evaluated by any specific quantitative estimates. It is recommended that the error between the operation of the virtual model and the operation of the real object should not exceed 5%. The use of digital twins solves another extremely important task-the optimization of business processes for the maintenance of an object of control and monitoring. At the same time, the task of training technical personnel for the maintenance of aviation equipment in the new conditions of digital transformation is also being solved. In a quality indicator is proposed that assesses the degree of trust in digital twins [13], [14]. Digital twin is "a virtual representation of objects and processes of the real world synchronized with them with a certain frequency and degree of accuracy." Trust in the "digital twin" should be viewed as a degree of "functional equivalence to a physical object". This does not exclude the indicator -accuracy. A key quality mechanism is the degree of integration of historical data and knowledge, as well as the ability to see the "big picture". Trust is assessed by 14 factors [15]. Trust is the probability of equivalence of the calculated (predicted) and real behavior (functionality) of the object under study under given conditions. The key function of the digital twin is "measurement and monitoring", which is described as a "unique advantage". The quality of a measurement is determined by the error or uncertainty. Ultimately, it is this parameter that determines the credibility of the digital twin.

An integral part of the digital twin is the model. Which solves the problems of control, safety, and forecasting [16]–[18]. The work analyzes the problem of modeling on the example of the experience of Airbus helicopters. The author of the work points out that "modeling a helicopter is an incredibly difficult task" and the calculation model must be "very accurate". A model is a very large complex of models, consisting of 500 individual models working in real time. In the mathematical software of the digital twin, the source code, which is subjected to constant control, acquires key importance. Mathematical, software and information support are systemic means of forecasting. Despite the estimates of forecasts given as "accurate forecasts", a quantitative measurement of accuracy is not indicated, from which it should be assumed that the system accuracy does not exceed 10%, which is an insufficient metrological level of quality.

Juang *et al.* [19], already in the near future, about half of large industrial manufacturers plan to use the technology of digital twins. This graphical model is a virtual implementation of the aircraft maintenance system. The most common aircraft are helicopters, which are successfully used in digital twin technology. The context model of the helicopter maintenance digital twin, in accordance with the technical regulations, systematically includes several digital subsystems [20], [21]. All local system digital twins use a single database-BigDate. As seen in Figure 1, the digital twin virtually aggregates the physical hardware of the original with the hardware of the digital twin. The physical equipment of a real object-the original includes on-board and external sensors, communication interfaces and other equipment. The information from the sensors after digital processing is recorded in the onboard memory of the aircraft. Next, the virtual part of the system begins to work in the form of a software package, which is the basic component of the digital twin. Continuous analysis of the current technical condition of the aircraft units with regulatory requirements. With the connection of the operational analysis system, security-critical events are predicted. Also, possible problems are identified at an early stage, when they have not yet reached a critical state. The context of the operation of the digital twin includes a separate simulation/system model for modeling various scenarios of the operation of a physical object [22]. Figure 1 presents the concept of the digital twin in the context of model-based systems engineering (MBSE) [23].

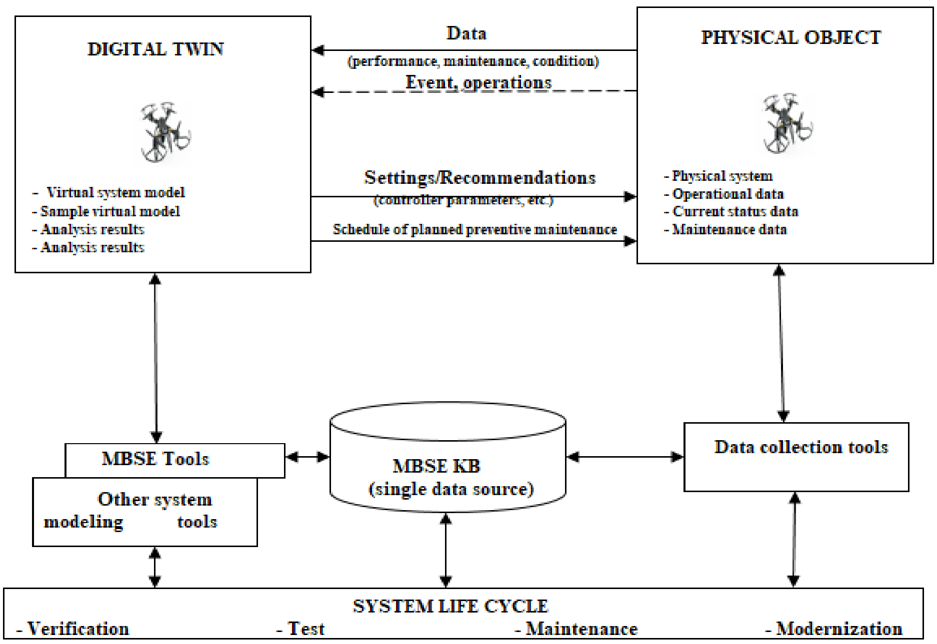

Figure 1. Conceptual model of the digital twin in the MBSE environment [23]

Mathematical modeling has now become a key component of digital twins. According to forecasts, soon, predictive maintenance by integrating digital twins with production processes will ensure the transition from routine maintenance to condition-based maintenance, will also significantly reduce operating costs and increase the fault tolerance of facilities. The use of mathematical and software for integrated product lifecycle management creates a new design approach called MBSE [24]. This approach moves the troubleshooting process to earlier stages of product design and operation. In this sense, the digital twin is a tool to radically reduce the risks of implementing projects of complex multi-parameter systems. Unlike traditional models, the digital twin closely links the real space and the virtual. In the proposed study, attention is focused on assessing the quality of management of complex technological processes (TP) for the maintenance and repair of aircraft units in a real aircraft repair enterprise. The main scientific and practical idea of the study is to study the degree of influence on the efficiency of work and training of service personnel of the methodology of digital twins.

3. METHODS

The work consists of theoretical studies based on a formal platform and experimental studies of real mass dynamic processes. Probability theory and mathematical statistics, simulation modeling, fuzzy set theory, methods of expert assessments. For the processing of experimental data, the apparatus of mathematical statistics and the professional software package statistica were used. At the final phase of the research, an assessment was made of the adequacy of theoretical premises to practical data from the field of operation of real objects. The contextual functional in the study considered the process of control.

The purpose of this article is to apply the methodology of digital twins in the educational process. The digital twins provide completely new opportunities for obtaining both theoretical and practical knowledge. The digital twin completely changes the way users interact with the device, giving them the freedom to experiment and come up with bold, innovative applications or prototypes.

4. RESULTS AND DISCUSSION

Currently, digital computer technologies, and in particular digital twins, significantly increase the efficiency of maintenance and repair of aircraft units, and in particular, helicopters. In this environment, software and especially statistical and simulation modeling play a key role [25]. Statistical modeling is one of the sections in the software for the digital transformation of the maintenance and repair of complex systems, since it is widely used in solving the following important problems:

a) Creation of technical regulations for TP for the assembly of aircraft units;
b) Development of optimal TP algorithm for assembling units;
c) Optimization and synthesis of TP.

As a result of the experiment, the effectiveness of the proposed mechanism and, in general, the digital twin in the educational system was obtained. The described innovative approach can be useful not only for educational programs in aviation, but also in other branches of engineering. The following information about each element is included in the technical regulations of the TP for the assembly of aircraft units: physical nature, place, sequence, parameters, characteristics, interaction, influence. It can also be considered: the idea of the study, description of dependencies, tables and graphs, initial conditions. The aircraft assembly assembly algorithm, considering the features of the TP, is created on the basis of a mathematical model and is presented in the form of a block diagram or a text description of operators-a group of elementary operations.

Operators by purpose are divided into the following subgroups:

- Basic-represent the description and functioning of models of real elements and processes under external influences, as well as imitation of elementary operations;
- Auxiliary-perform calculations for the implementation of the main operators;
- Service-provides synchronization and interaction of operations, registration of measurement results and processing.

When modeling the TP of assembling aircraft units, the following operators are used:

- Computing;
- Generating random processes and numbers;
- Formation of stabilized characteristics;
- Readers of the number of elements and processes.

When building a statistical model, operations are usually divided into single processes-elementary acts.

When modeling aircraft units, operations are carried out on tools and non-separable parts according to the principle of master and slave. As a result of which the characteristics of the leading part are changed due to attachment, i.e. $W \rightarrow n$ (n is the number of elements in the aggregate) and the number of slaves is reduced, i.e. $V \rightarrow 0$.

Dependence of aircraft assembly parameters as shown in (1):

$$P_j = f(a_j, a_{i1}, a_{i2}, \dots, a_{iK}, c_1, c_2, \dots, c_R) \quad (1)$$

where a_j is a parameter characterizing the preparation and installation of the leading part W for assembly of the j-th unit;
$a_{i1}, a_{i2}, \dots, a_{iK}$– Parameters of driven parts V;
K is the number of driven parts;
$c_2, \dots, c_R$– Random tool parameters;
R is the number of tools needed to assemble the unit.

In (2) duration of the assembly of the aircraft unit is represented as a sequential sum of time intervals.

$$t_j^{mes} = t_j^{beg} + \sum_{k=1}^{K} t_j^{u}(k) + \sum_{k=1}^{K} t_j^{pod}(k) + \sum_{r=1}^{R} t_j^{ins}(r) + t_j^{reg} \quad (2)$$

where t_j^{beg} – the time interval for preparing the unit for assembly;
$t_j^{u}(k)$ – installation interval of the k-th part;
$t_j^{pod}(k)$ – interval for preparing a part for assembly;
$t_j^{ins}(r)$ – time interval of work with the r-th tool;
t_j^{reg} – adjustment time of the unit with the transition to the assembly of the subsequent unit.

The use of digital twins, as the practice of using this technology in various industries, significantly increases the competence of specialists, and as a result, the overall efficiency of production processes. To evaluate the effectiveness of digital twins in this subject area, special studies were carried out in specific production conditions of an aircraft repair enterprise. The following results were obtained.

a) The total number N of digital twins of aircraft units DT_N for an aircraft repair enterprise is determined by the following relationship as shown in (3):

$$DT_N = DT_{N1}^{Mech} + DT_{N2}^{El}, \quad (3)$$

where DT_{N1}^{Mech} - mech are digital twins of units with mechanical elements with a total of N1, intended for training mechanics;
DT_{N2}^{El} - digital twins of units with radio-electronic components with a total of N2, intended for training electronics engineers.

b) All production processes for the repair of aviation equipment are implemented in strict accordance with the technical map, so they are influenced by various factors:
- Random disturbances;
- The correct sequence of organization of production;
- Equipment reliability;
- Synchronization of processes.

Under these conditions, it is necessary to determine an assessment or parameter that would effectively and correctly reflect the knowledge and practical competencies of students. Naturally, certification must be carried out for mechanics and electronics engineers separately. Regardless of the type of certification, two options are used with a fixed number of units, i.e. $N = K = const$. The first option is traditional and, of course, the most reliable. However, the use of digital twins has a significant effect and benefits for learning.

At aircraft repair enterprises, it is proposed to use the time of assembly or disassembly operations as an estimated parameter. It is all the factors associated with inaccuracy or incorrect order of assembly of units that will affect the selected parameter:
- In the first case, t^{RO}-certification time with training on real objects RO, the value is determined empirically-based on the recommendations of enterprise specialists as shown in (4).

$$t^{RO} = \sum_{n=1}^{N} t_n^{RO} \quad (4)$$

- In the second $t^{\Sigma} = t^{DT} + \Delta t^{RO}$-certification time equal to the sum of training time (t^{DT})on digital twins and an additional time interval on real objects (Δt^{RO}) while maintaining the main condition for quality learning $t^{RO} = t^{\Sigma}$, i.e. in accordance with the expression as shown in (5):

$$t^{\Sigma} = \sum_{k=1}^{K1} t_k^{DT} + \sum_{k=1}^{K2} t_k^{RO}, \quad (5)$$

where K1-is the number of digital twins; K2-is the number of real aggregates.

c) The additional training time Δt^{RO} can be effectively represented as a relative coefficient as shown in (6).

$$[\Delta t^{RO}] = (t^{RO} - t^{DT})/t^{RO} \quad (6)$$

If $[\Delta t^{RO}] \geq -1$, then the student must be sent for re-training on real objects, since he is not inclined to use digital technologies in training. If $-1 \leq [\Delta t^{RO}] \leq 1$, then the trainee must pass successive trainings (trainings) on real objects R in accordance with the expression as shown in (7).

$$R = f\left((t^{RO} - t^{DT})/t^{RO}\right) \quad (7)$$

Consider the application of the method of analyzing the results of certification of students using digital twins of the assembly of aircraft units. As a result of the experiment at the production site of the aircraft repair enterprise, the data presented in Tables 1 and 2 were obtained. The data of the results of certification of mechanics are presented in Table 1. The results of certification of electronics engineers are presented in Table 2. Figure 2 presents the empirical data in graphical form.

Table 1. Results of certification of mechanics

Students	Certification time on real objects ($\mathbf{t^{RO}}, \mathbf{sec}$..)	Certification time for DT ($\mathbf{t^{DT}}, \mathbf{sec}.$)	Training time factor $[\Delta \mathbf{t^{RO}}]$	Number of trainings (R)
1	4,800	4,829	-0.006042	2
2	4,800	4,869	-0.014375	3
3	4,800	4,737	0.013125	0
4	4,800	4,922	-0.025417	5
5	4,800	4,800	0.000000	2
6	4,800	4,834	-0.007083	2
7	4,800	4,773	0.005625	1
8	4,800	4,787	0.002708	1
9	4,800	4,819	-0.003958	2
10	4,800	4,819	-0.003958	2
11	4,800	4,797	0.000625	2
12	4,800	4,790	0.002083	1
13	4,800	4,808	-0.001667	2
14	4,800	4,810	-0.002083	2
15	4,800	4,800	0.000000	2
16	4,800	4,936	-0.028333	5
17	4,800	5,156	-0.074167	10
18	4,800	4,821	-0.004375	2
19	4,800	5,046	-0.051250	7
20	4,800	4,882	-0.017083	4
21	4,800	4,821	-0.004375	2
22	4,800	5,075	-0.057292	8
23	4,800	4,836	-0.007500	3
24	4,800	4,728	0.015000	0
25	4,800	4,770	0.006250	1
26	4,800	4,828	-0.005833	2
27	4,800	4,876	-0.015833	3
28	4,800	4,846	-0.009583	3
29	4,800	5,001	-0.041875	6
30	4,800	4,850	-0.010417	3
31	4,800	4,839	-0.008125	3
32	4,800	4,866	-0.013750	3
33	4,800	4,877	-0.016042	3
34	4,800	4,803	-0.000625	2
35	4,800	4,875	-0.015625	3
36	4,800	4,809	-0.001875	2
37	4,800	4,831	-0.006458	2
38	4,800	4,846	-0.009583	3
39	4,800	4,790	0.002083	1
40	4,800	4,839	-0.008125	3
41	4,800	4,769	0.006458	1
42	4,800	4,799	0.000208	2
43	4,800	4,786	0.002917	1
44	4,800	4,845	-0.009375	3
45	4,800	4,876	-0.015833	3
46	4,800	4,750	0.010417	1
47	4,800	4,855	-0.011458	3
48	4,800	4,784	0.003333	1
49	4,800	4,794	0.001250	2
50	4,800	4,797	0.000625	2

Table 2. Results of certification of electronics engineers

Students	Certification time on real objects (t^{RO}, sec.)	Certification time for DT (t^{DT}, sec.)	Coefficient of additional training time [Δt^{RO}]	Number of trainings (R)
1	3,400	3,376	0.007059	1
2	3,400	3,423	-0.006765	4
3	3,400	3,449	-0.014412	6
4	3,400	3,462	-0.018235	6
5	3,400	3,484	-0.024706	8
6	3,400	3,402	-0.000588	3
7	3,400	3,437	-0.010882	5
8	3,400	3,426	-0.007647	4
9	3,400	3,401	-0.000294	3
10	3,400	3,420	-0.005882	4
11	3,400	3,406	-0.001765	3
12	3,400	3,441	-0.012059	5
13	3,400	3,422	-0.006471	4
14	3,400	3,408	-0.002353	3
15	3,400	3,411	-0.003235	3
16	3,400	3,469	-0.020294	7
17	3,400	3,429	-0.008529	4
18	3,400	3,483	-0.024412	8
19	3,400	3,437	-0.010882	5
20	3,400	3,424	-0.007059	4
21	3,400	3,435	-0.010294	5
22	3,400	3,445	-0.013235	5
23	3,400	3,524	-0.036471	10
24	3,400	3,434	-0.010000	5
25	3,400	3,435	-0.010294	5
26	3,400	3,486	-0.025294	8
27	3,400	3,414	-0.004118	3
28	3,400	3,438	-0.011176	5
29	3,400	3,429	-0.008529	4
30	3,400	3,453	-0.015588	6
31	3,400	3,355	0.013235	0
32	3,400	3,439	-0.011471	5
33	3,400	3,377	0.006765	1
34	3,400	3,408	-0.002353	3
35	3,400	3,403	-0.000882	3
36	3,400	3,398	0.000588	3
37	3,400	3,437	-0.010882	5
38	3,400	3,359	0.012059	0
39	3,400	3,433	-0.009706	5
40	3,400	3,378	0.006471	1
41	3,400	3,403	-0.000882	3
42	3,400	3,397	0.000882	2
43	3,400	3,475	-0.022059	7
44	3,400	3,417	-0.005000	4
45	3,400	3,481	-0.023824	7
46	3,400	3,432	-0.009412	5
47	3,400	3,444	-0.012941	5
48	3,400	3,448	-0.014118	6
49	3,400	3,443	-0.012647	5
50	3,400	3,442	-0.012353	5

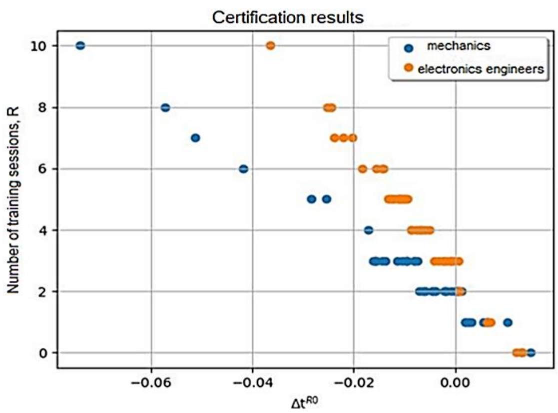

Figure 2. Results of certification

From the graphs in Figure 2, we can conclude that there is a relationship between $[\Delta t^{RO}]$ and the number of trainings R. If we assume that the relationship is approximately linear, then it can be represented as a straight line on this graph. It will be possible to predict the required number of trainings along this straight line, if $[\Delta t^{RO}]$ is known. Those solve the regression problem.

The linear algorithm in regression problems can be represented as shown in (8):

$$a(x) = w_0 + \sum_{i=1}^{d} w_i x_i, \tag{8}$$

where w_0 is a free term; w_i are feature weights; x_i - signs.
In (9) can be represented in a more compact form by introducing an additional feature (d + 1) equal to 1 for each object.

$$a(x) = \sum_{i=1}^{d} w_i x_i = \langle w_i x_{i_i} \rangle, \tag{9}$$

In (10) can be considered as a scalar product of two vectors w and x. The variance is chosen as the error function:

$$Q\langle w, x \rangle = \frac{1}{l} \sum_{i=1}^{1} (\langle w, x_i \rangle - y_i) \tag{10}$$

where l – is the total number of samples, y – is the predicted value.

In accordance with (11), the training of a linear regression model can be represented in a matrix form:

$$Q\langle w, x \rangle = \frac{1}{l} \|X_w - y\| \rightarrow \min_w \tag{11}$$

Numerical optimization methods were used to obtain the regression model. Since function (10) is convex and smooth, the gradient descent method can be applied to find its minimum. The formula for calculating the gradient in the general case as shown in (12):

$$\nabla_w Q\langle X, w \rangle = \frac{2}{l} X^T (X_w - y) \tag{12}$$

as a result, in accordance with the presented methodology, linear regression models were obtained for the certification process of mechanics and electronics engineers:

$$Rmeh = -109{,}4 \times \Delta tR0 + 1{,}658,$$
$$Relec = -207{,}8 \times \Delta tR0 + 2{,}620.$$

Figure 3 shows the result of solving the regression problem according to the available data.

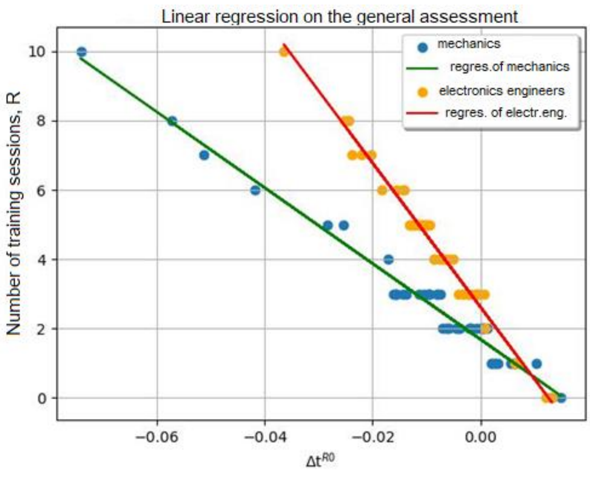

Figure 3. Regression model for the validation process

5. CONCLUSIONS

The solution to the problem of digital transformation of the aviation industry in the phase of aircraft maintenance and repair, where the key point is the digitization of operational documentation with the creation of a digital document and the creation of application software in the form of a digital twin in a virtual reality environment, is considered. The concept of a digital twin is presented in the context of model-based systems design, which includes the features of helicopter maintenance according to technical regulations and using big date. The digital twin virtually aggregates the physical equipment of the original: on-board and external sensors, communication interfaces and other equipment. On the basis of statistical modeling technologies, as an advanced mathematical tool for digital transformation, an aircraft assembly model has been developed, in which temporal characteristics are qualitative assessments of learning processes and the effectiveness of digital twins.

The digital twin makes it possible to conduct training activities that are difficult to implement in conventional laboratory classes. The 3D visualization and interactive features implemented by DT technology can be used to produce tangible learning outcomes: i) development of skills for solving real production problems; ii) study of engineering tasks in various modes that cannot be organized in a traditional classroom or laboratory due to various reasons, such as cost or safety; iii) support for the creative approach of students, as this provides an opportunity for understanding innovative technologies. An analysis of the possibilities of using the digital twin in education made it possible to identify a conceptual approach to the implementation of the mechanism of the DT educational application for the repair of aviation equipment, based on the interval repetition method. The presented mechanism can be applicable to the development of DT training software in other areas.

The results of experimental studies are presented using the method of analyzing the certification of students based on digital twins when assembling aircraft units. It has been established that at the production site of an aircraft repair enterprise it is effective to apply training at the first stage using digital twins, and at the second stage using real objects. Based on the analysis of experimental data, regression models of the relationship between the number of trainings at the second stage and the relative coefficient of training time for successful certification of mechanics and electronics engineers were obtained.

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