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IMPLEMENTATION OF REENGINEERING TECHNOLOGY TO REDUCE THE TERMS OF THE TECHNICAL PREPARATION OF MANUFACTURING OF AVIATION TECHNOLOGY ASSEMBLIES

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The object of this study is the technical preparation of manufacturing (TPM) of aviation technology (AT) using reengineering technology. The task to reduce the terms of TPM AT was tackled while solving direct and inverse problems of shape formation involving reengineering. The study is based on the equation for calculating the labor intensity of creating an assembly unit (AU) as a mathematical model for the formation and accumulation of components of the total labor intensity at all stages. The following results are reported: a scheme has been proposed for linking homogeneous components of an article obtained using the loft-template method (LTM) with digital mock-up (DMU) when applying the reengineering method. The scheme summarizes and structures the reengineering technology to solve direct and inverse shape-formation problems and could be used to solve the tasks of prototyping, manufacturing, and refurbishment of tooling, as well as article control at all stages of production. An example of the helicopter stabilizer shows that when solving the direct shape-formation problem, the labor intensity is from 294.94 to 315.06 man-hours, and when solving the inverse problem – from 194.78 to 213.22 man-hours. A comparative analysis of the labor intensity of TPM revealed a difference of 1.5 times in favor of the labor intensity of solving the inverse problem. Comparing the labor intensity of creating DMU for the stabilizer of a helicopter has made it possible to establish that the labor intensity of solving the inverse problem is 3.7 times less than the labor intensity of solving a direct problem. Recommendations for reducing the terms of TPM AT with the use of reengineering are given. The results could be used to assess the labor intensity and timing of TPM AT and mechanical engineering objects in general when using reengineering technology

Keywords: technical preparation of production, reengineering, assembly unit, analytical standard, aviation technology

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1. Introduction

The use of the reengineering method in industry makes it possible to solve a number of problems in the manufacture, control, repair, and modernization of aviation technology (AT). According to ICAO [1], during the periods of international crises (the crisis in the Persian Gulf of 1990–1993, the terrorist attacks of 11.09.2001, the financial crisis of 2007–2009), passenger air traffic is significantly reduced. As a result of the COVID-19 pandemic, international passenger traffic fell sharply by 60 % in 2020, bringing total air travel back to 2003 levels. This forces aircraft operators to convert passenger AT into cargo AT. At the same time, first, the AT, which was produced 10 or more years ago in the context of the development of technologies at that time, is subject to modernization or conversion. The modern approach to designing AT is based on the use of digital technologies, so any conversion or modernization of AT begins with bringing the existing documentation and data carriers to electronic ones. Typically, we are talking about the digitization of AT made using related linkage methods. At the same time, the traditional loft-template method (LTM) provides a deviation of external contours equal to ±2.0 mm [2].

Modern aircraft production involves the use of numerically controlled machines (CNCs), coordinate measuring machines (CMMs), 3D scanners, digitizers, laser systems, robotics, or automated equipment, etc. Such a fleet of equipment helps digitize and reproduce real objects, and the technology based on them is termed reengineering. The reengineering technology implies 3D scanning of AT, conversion of the resulting scanned surfaces into portraits, the construction of analytical standards (ASs) and product models (PMs) [3].

This is especially true when repairing and modernizing the AT structure, when installing new equipment on board, or for integrating modern technologies into existing systems [4].

The term «analytical standard» refers to a model developed by the means and tools of CAD systems using spline geometry. AT objects of any degree of complexity, designed using the apparatus of spline geometry, have unambiguous description. This and many other positive properties can explain the widespread use of CAD/CAM systems by machine-building enterprises in modern production. The use of AS made it possible to change the design process and greatly simplifies the algorithms of shape-formation processes and control over their implementation.

The creation of AT implements the direct task of shape formation when the DMU is initially built, and, according to it, its PM and the article itself. Reengineering solves the inverse problem of shape formation when a real physical object becomes an electronic model [5].

Despite the widespread use of reengineering technology in the aviation industry, one of the main issues in the implementation of reengineering is the technical preparation of manufacturing (TPM), which should be introduced into the existing established production. Therefore, the coordination of direct and inverse shape formation problems in the production of AT is a relevant task.

2. Literature review and problem statement

The reduction of TPM terms is provided, first of all, through information automated support for production. Paper [6] reports the experience of implementing Smart Inspection Tools designed for the manufacture of fuselage panels within the framework of the LABOR project. The focus is on the development of two Smart Inspection tools used to bind the robot to the geometry of the panel and to check the quality of the holes made. The use of various control technologies that guarantee strict compliance with the project specifications is shown. The effectiveness of the application of the reported information automated support of production in [6] during the implementation of the reverse problem is obvious but the effectiveness of its implementation in existing production technologies that solve direct problems is not shown. The authors of works [7, 8] developed this idea in virtual reality technologies but without practical confirmation of the simulation results.

The authors of [9] followed the path of Boeing, Ford, General Motors, and Volkswagen, which universally apply virtual engineering technologies at the stages of technological preparation of production. The results of approbation of the VR IC.IDO virtual engineering system on the door of the aircraft, in which the direct and inverse problems are interconnected, are shown. The authors argue that the use of the VR system will shorten the time and reduce the costs of TPM, as well as partially or completely eliminate errors in production. However, despite the stated advantages, the cited paper does not show the relationship of the virtual engineering VR IC.IDO with CAD/CAM/CAS systems. Article [10] reports the results aimed at reducing the time of TPM by increasing the efficiency of CAD/CAM/CAS-systems through the use of the Microsoft Visual Studio subroutine. The authors state that the main purpose of the subroutine is the preliminary adjustment of the cutting mode and the geometry of the chips being removed, depending on the created trajectory of the tool when milling the surface of a complex shape. This adjustment with the Microsoft Visual Studio routine reduces the number of «test runs» and part defects. The reduction of TPM terms is implemented precisely due to the preliminary adjustment with access to the final program in the CAM system. It is worth noting that the proposal of the authors of [10] is doubtful since a forecast has not been made of how much reduction in the terms of TPM can be counted on and what time will be spent on the adjustment itself. The review paper [11] describes ways to reduce TPM terms, among which the transition to electronic models and automation is shown, but there are no specific calculations or procedures for determining the necessary timing of TPM when using engineering tools.

The practical implementation of AT part reengineering is shown in the next few publications. In [12], reengineering is presented on the example of scanning a propeller by a 3D scanner with the subsequent creation of DMU and a 3D model. In [13], with the help of the Mistral 070705 (USA) CMM, the reengineering technology is implemented not only to create a propeller DMU but also to build a molding tooling with its subsequent manufacture on CNC. There, reengineering solves the task of prototyping aviation objects (AOs) based on the created DMU. Work [14] showed the possibility of implementing the technology of reengineering when controlling the keel of a light aircraft and the equipment for its manufacture. In [15], reengineering is used in the intermediate stages of control over the shaping of the aircraft panel, which simplifies data analysis and helps adjust the manufacturing technology to ensure the predefined geometric accuracy. In comparison with [12, 13], Artec Studio (Luxembourg) software is used for reengineering in [14, 15], which is easily integrated with CAD/CAM/CAS systems and does not require the development of an additional interface. Papers [12–15] demonstrate the use of reengineering technology at various stages of AT production, including at TPM, by solving and combining direct and inverse problems. Despite the practical value of the results obtained, there are no specific data on time savings in their application in existing production.

Analyzing works [6–15], it can be concluded that many authors avoid specifying quantitative characteristics when forming DMU AO when solving direct and inverse problems. At the same time, there are no complete data on the timing of TPM in the literature sources, and there is also no information on a possible reduction in TPM terms when using reengineering technology. According to many authors, a significant reduction in TPM terms is achieved with the simultaneous widespread use of modern means of receiving, transmitting, and processing information. Therefore, there is reason to believe that it is necessary to know exactly the time norms for reengineering when solving direct and inverse problems, which will determine the timing of TPM, which confirms the relevance of research in this area.

3. The aim and objectives of the study

The purpose of this study is to develop ways to implement reengineering technology to reduce the time of AT TPM when applying reengineering. This will make it possible to shorten the production time and reduce the cost of AT.

To accomplish the aim, the following tasks have been set:

– to develop a scheme for linking homogeneous AOs obtained by dependent linking methods with DMU when applying reengineering;

– to assess the complexity of work on the creation of DMU AU of a helicopter in solving the direct and inverse problem of shape-formation;

– to perform a comparative analysis of the labor intensity of creating a helicopter DMU AU and the labor intensity of TPM in solving the direct and inverse problems of shape-formation.

4. The study materials and methods

4. 1. Procedure for determining the labor intensity of the reengineering process

The subject of our study is the reengineering of AT assembly units.

The object of the study is the labor intensity of TPM in the implementation of reengineering.

The research is based on the equation for calculating the labor intensity of creating the components of AT (parts and AUs) using the reengineering method as a mathematical model of the formation and accumulation of constituent time periods at all stages of the process. Based on statistical data [16], the general equation for calculating the labor intensity of assembly for solving practical tasks requires the decomposition of all components into elementary components. The components of the equation were determined from the analysis of all the essential features of an assembled AO and technological factors in the process of TPM and production. It is accepted that the total labor intensity of reengineering is a set of links-periods of labor intensity for all operations of the reengineering process. This approach has made it possible to perform the calculation according to the standard procedure from the theory of dimensional chains [17] to select ISO, DIN. With the known parameters of the errors of the constituent links-periods, the inverse problem is solved, and, with the direct problem, the parameters of the error of the total labor intensity of the process are initially known.

The value of the final scattering field of the random variable of the total labor intensity of a process [18, 19] is determined from the formula:

$$\delta_\Sigma = \frac{1}{K_\Sigma}\sqrt{\sum_{i-1}^{m-1} \xi_i^2 K_i^2 \delta_i^2}, \qquad (1)$$

where K_Σ, K_i are the coefficients of relative scattering of the errors of the closing and i-th component links of the scattering fields; δ_i is the scattering field of errors or tolerances of the components A_i of the chain (labor intensity); $m-1$ is the number of constituent links; ξ_i is the gear ratio of the i-th link $\left(\xi_i = \partial A_\Sigma / \partial A_i\right)$.

The resulting value of the deviation of the middle of the field of tolerance of labor intensity:

$$\Delta_{0\Sigma} = \sum_{i=1}^{m-1} \xi_i \left(\Delta_{0i} + \alpha_i \frac{\delta_i}{2}\right) - \alpha_\Sigma \frac{\delta_\Sigma}{2}, \qquad (2)$$

where α_Σ, α_i are the coefficients of relative asymmetry of the scattering curves of the errors of the closing and i-th links of the size chain, respectively; δ_Σ is the error scattering field or tolerance of the closing link (labor intensity) of the chain; $\Delta_{0\Sigma}$, Δ_{0i} are the coordinates of the middles of the scattering fields of the links (labor intensity) of the chain.

K_i coefficients are found from formulas in [19]:

$$K_i = \frac{\sigma_i}{\sigma_{n.s.l.i}} = \frac{6\sigma_i}{\delta_i}, \quad 1 \le K_i \le \sqrt{3}, \qquad (3)$$

where Σ_i, $\Sigma_{n.s.l.i}$ are the standard deviations of the actual and normal scattering laws of the i-th link of the size chain. For the normal law of scattering of the i-th link of the size chain, as is known, $\Sigma_i = 6\Sigma\ \Sigma_{n.s.l.i}$. For the actual law described by the Gaussian curve, $K_i = 1$.

The coefficient of displacement of the center of the grouping of errors from the middle of the scattering field of errors is determined from the formula:

$$\alpha_i = \frac{M_{\Delta_i} - \Delta_i}{0.5\delta_i}, \quad -1 < \alpha_i < +1, \qquad (4)$$

where $M_{\Delta i}$ is the expected value (arithmetic mean, center of grouping) of the errors of the i-th link.

4. 2. Algorithm for solving inverse shape-formation problems in the technical preparation of manufacturing

The solution to direct and inverse problems is based on a single source of information – DMU.

The use of DMU for the integrated solution to design and technological problems helps reduce the overall labor intensity of TPM [20].

The algorithm for solving inverse shape-formation problems at TPM for a part and AU is shown in Fig. 1, which demonstrates the creation of an electronic description based on the real physical existing node and part.

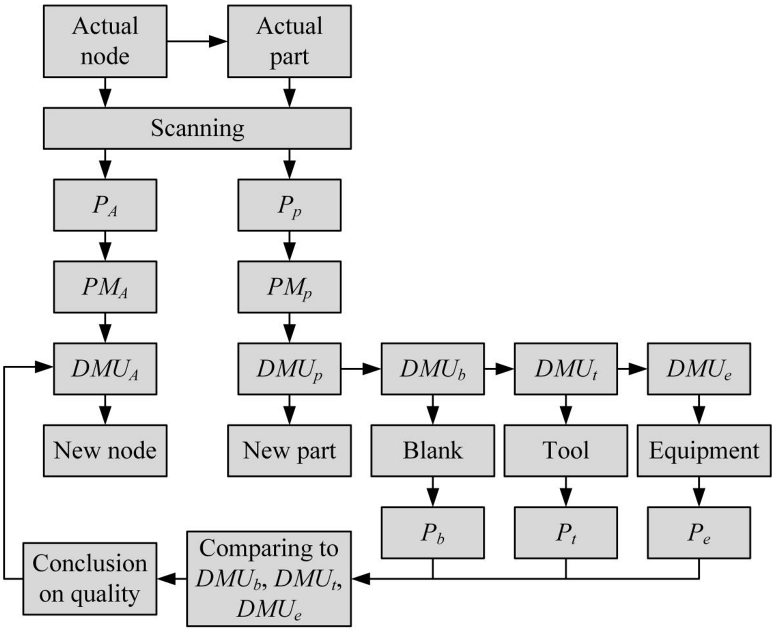

Fig. 1. Algorithm for solving inverse problems of shape formation in the technical preparation of aviation production

The algorithm includes the following stages of creation:

– portraits of the assembly P_a and of the part P_p;

– models of the processes of assembly MP_a and manufacture of the part PM_p, considered as PM;

– digital mock-up of the part DMU_p, the blank DMU_b, the tool DMU_t, and the equipment DMU_e;

– portraits of the blank P_b, the tool P_t and the equipment P_e;

– control – comparison of all obtained portraits P_b, P_t and P_d with their digital mock-up DMU_p, DMU_b, DMU_t and DMU_e;

– conclusion on the quality of parts with the prospect of creating digital mock-up for assembly DMU_A for the subsequent manufacture of a new AO with new parts.

5. Results of studying the implementation of reengineering technology in the technical preparation of manufacturing

5. 1. Devising a scheme for linking homogeneous articles obtained by the loft-template method with the digital mock-up during reengineering

A scheme for linking homogeneous *AO* obtained using LTM with *DMU* when applying reengineering is shown in Fig. 2.

In the scheme, *AU* 1–4, those obtained using LTM, are shown as representatives of homogeneous *AO*. After scanning these AU, their portraits P_{AUi} were obtained, and then, based on process models, the digital mock-up DMU_{AU1}, DMU_{AU2}, DMU_{AU3}, DMU_{AU4} were built. The process of constructing these standards includes building a triangulation model and base surfaces, forming, editing, and controlling the model, and, finally, building a reference. Further, according to *DMU* of homogeneous *AO*, a generalized *DMU* of the article assembly DMU_A is built. The DMU_A production model contains conditions for ensuring the interchangeability and accuracy of new *AO*. To meet such conditions, it is possible to partially change the design of *AU* or use methods to compensate for errors during assembly. Such an DMU_A makes it possible to ensure the creation of an assembly device for obtaining new *AU* that meet the requirements for their assembly in a structure assembled earlier using *LTM* to ensure interchangeability.

Confirmation of the adequacy and reliability of AT is provided by the comparison of the portrait of the assembled new AO with the portrait of previously obtained carriers of sizes.

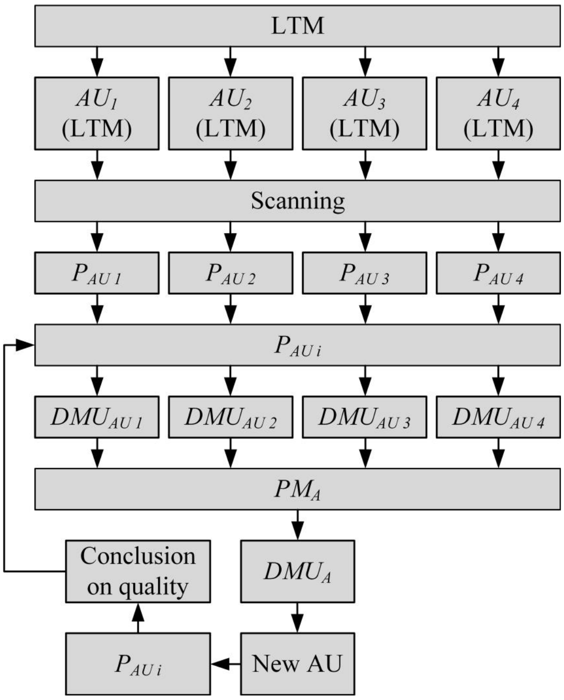

Fig. 2. Scheme of linking homogeneous aviation objects obtained using the loft-template method with the digital mock-up when applying reengineering

5. 2. Estimating the labor intensity of creating the digital mock-up of an assembly unit for the inverse and direct problems of shape formation

The assessment of the complexity of work on the creation of DMU AU of the helicopter when solving the inverse problem of shape formation is carried out on the example of the helicopter stabilizer when the assembly is performed in an assembly device with basing from the frame. Setting the norms of labor intensity for operations was carried out by the method of expert evaluation [16], as well as our practical experience in conducting experiments. Given that the time norms determined by the method of expert evaluation acquire the character of random variables, dependences were applied to these values for processing and summing random variables from probability theory [19]. To calculate the labor intensity of the inverse shape-formation problem, subject to the use of reengineering, the operational technology of TPM was developed and the operation time for the helicopter stabilizer was set (Table 1).

Table 1 includes the following symbols:

– $t_{i\ \max}$ is the maximum labor intensity of the operation;

– $t_{i\ \min}$ is the minimum labor intensity of the operation;

– Δ_i is the coordinate of the middle of the scattering field of errors of the *i*-th link of the dimensional chain;

– $\delta_i/2$ is the half of the field of scattering errors or tolerance A_i of the constituent link of the dimensional chain (labor intensity);

– A_i is the transmission coefficient of the *i*-th component of the scattering fields;

– k_i is the coefficient of relative scattering of errors of the *i*-th component of the scattering fields;

– α_i is the coefficient of displacement of the center of grouping of errors from the middle of the scattering field of errors;

– $A_i \alpha_i \delta_i/2$ is the magnitude of the displacement of the center of the grouping of errors from the middle of the field of scattering of errors;

– $A_i \Delta_i$ is the value of the transmission of the coordinates of the middle of the scattering field of errors of the *i*-th link;

– $k_i^2 \left(\delta_i/2\right)^2 A_i^2$ is the magnitude of the standard deviation of the *i*-th component of the scattering fields.

From the calculations, it follows that the coordinate of the middle of the field of total scattering of labor intensity $\Delta_{0\Sigma}$=204 h, and half of the scattering field of errors of the total labor intensity $\delta_\Sigma/2$=9.22 h. Consequently, the maximum estimated labor intensity of the implementation of the inverse problem, obtained by the theoretical-probabilistic method, is 204+9.22=213.22 h, the minimum estimated labor intensity of the implementation of the inverse problem is 194.78 hours.

The results of calculating the time of solving a direct problem by the theoretical-probabilistic method necessary to create a helicopter stabilizer using reengineering are given in Table 2. The values of the duration of individual operations are taken from the reference data and publications of the authors on the topic of TPM [15, 17].

From the calculations, it follows that the coordinate of the middle of the field of total scattering of labor intensity $\Delta_{0\Sigma}$=305 h, and half of the scattering field of errors of total labor intensity $\delta_\Sigma/2$=10.06 h. Consequently, the maximum estimated labor intensity of the implementation of a direct problem obtained by the theoretical-probabilistic method is 305+10.06=315.06 h, the minimum estimated labor intensity of the implementation of a direct problem is 294.94 hours.

Table 1

Results of calculating the labor intensity of reengineering for the helicopter stabilizer when solving the inverse problem of shape formation

No. of entry	Technological operation	$t_{i\,\max}$, $t_{i\,\min}$, man-hour	Δ_i	$\delta_i/2$	A_i	k_i	α_i	$A_i\,\alpha_i\,\delta_i/2$	$A_i\,\Delta_i$	$k_i^2\left(\delta_i/2\right)^2 A_i^2$
1	Formulating the conditions of the problem, choosing an object	+5, +2	3.5	1.5	+1	1.4	0	0	3.5	4.41
2	Scanning object surfaces	+3, +2	2.5	0.75	+1	1.0	0	0	2.5	0.56
3	Creating and editing a triangulation model	+8, +6	7	1.0	+1	1.0	0	0	7	1.0
4	Formation and control of basic surfaces	+4, +3	3.5	0.5	+1	1.0	0	0	3.5	0.25
5	Building a 3D model	+12, +9	10.5	1.5	+1	1.0	0.5	0.5	10.5	2.25
6	3D model control and refinement	+15, +6	10.5	4.5	+1	1.0	0.5	0.5	10.5	20.25
7	Design of blank equipment	+50, +40	45	5	+1	1.0	0	0	45	25.0
8	Production of blank equipment	+24, +24	24	0	+1	1.4	0	0	24	0
9	Design of assembly equipment	+25, +20	22.5	2.5	+1	1.0	0	0	22.5	6.25
10	Production of assembly equipment	+80, +70	75	5.0	+1	1.4	0	0	75	25.0
Σ		+226, +182	–	–	–	–	–	1.0	204	84.97

Table 2

Results of calculation of the labor intensity of reengineering for the helicopter stabilizer when solving the direct problem of shape formation

No. of entry	Technological operation	$t_{i\,\max}$, $t_{i\,\min}$, man-hour	Δ_i	$\delta_i/2$	A_i	k_i	α_i	$A_i\,\alpha_i\,\delta_i/2$	$A_i\,\Delta_i$	$k_i^2\left(\delta_i/2\right)^2 A_i^2$
1	Mathematical description of the external forms of helicopter *AU*	+20, +15	17.5	2.5	+1	1.4	0	0	17.5	12.25
2	Creation of digital models of frame parts	+50, +45	47.5	2.5	+1	1.0	0	0	47.5	6.25
3	Development of design division schemes	+25, +20	22.5	2.5	+1	1.0	0	0	22.5	6.25
4	Creating *AU* models	+26, +19	22.5	3.0	+1	1.0	0.5	1.5	22.5	9.0
5	Product assembly check	+18, +12	15	3.0	+1	1.0	0.5	1.5	15	9.0
6	Formation of the *DMU* of product	+15, +12	13.5	1.5	+1	1.0	0.5	1.5	13.5	2.25
7	Design of blank equipment	+50, +40	45	5.0	+1	1.0	0	0	45	25.0
8	Production of blank equipment	+24, +24	24	0	+1	1.4	0	0	24	0
9	Design of assembly equipment	+25, +20	22.5	2.5	+1	1.0	0	0	22.5	6.25
10	Production of blank equipment	+80, +70	75	5.0	+1	1.4	0	0	75	25.0
Σ		+333, +277	–	–	–	–	–	4.5	305	101.25

5. 3. Comparative analysis of the labor intensity of creating the digital mock-up of the assembly unit and technical preparation of manufacturing

Analyzing the calculation data when solving the direct (Table 2) and inverse (Table 1) problems, the total labor intensity of creating an AU on the example of a helicopter stabilizer with an inverse task is 1.5 times less than when creating the same AU by the direct task method. If we compare the estimated labor intensity of the formation of DMU with direct and inverse problems, then, in the latter case, the DMU can be performed 3.7 times faster than when solving a direct problem. This is explained by the fact that during scanning, a ready-made technical solution is formed, in which many technical issues have already been resolved. The process of digitizing the finished solution with the help of a scanner and special software makes it possible to create DMU of the structure much faster and to ensure the production, modernization, or repair of AO, which was previously manufactured by LTM without the use of computer technologies. For clarity, the results of calculating the labor intensity of work on the creation of DMU (without taking into consideration half of the scattering field of errors of the total time δ_Σ) when solving the direct and inverse problems of shape formation are shown graphically in Fig. 3.

The plot (Fig. 3) demonstrates that scanning and processing the results when solving the inverse shape-formation problem is much faster to obtain *DMU* and start producing equipment for the manufacture of *AU*s. The variation in the execution time values in the first six stages of work is explained by the qualifications of the performers who perform the scanning and processing of the results.

When performing a direct problem, more time is required to perform individual stages due to the need to coordinate decisions with all contractors who are involved in the design and preparation of production of a would-be *AO*. It should be noted that manufacturers claim that the development of

DMU does not require much effort since many CAD/CAM systems have already embedded bases with models. As a rule, the systems can create models of missing equipment [21, 22]. Therefore, after performing *TPM*, all units of *CNC* equipment and all technological equipment can be included in the information system of the enterprise.

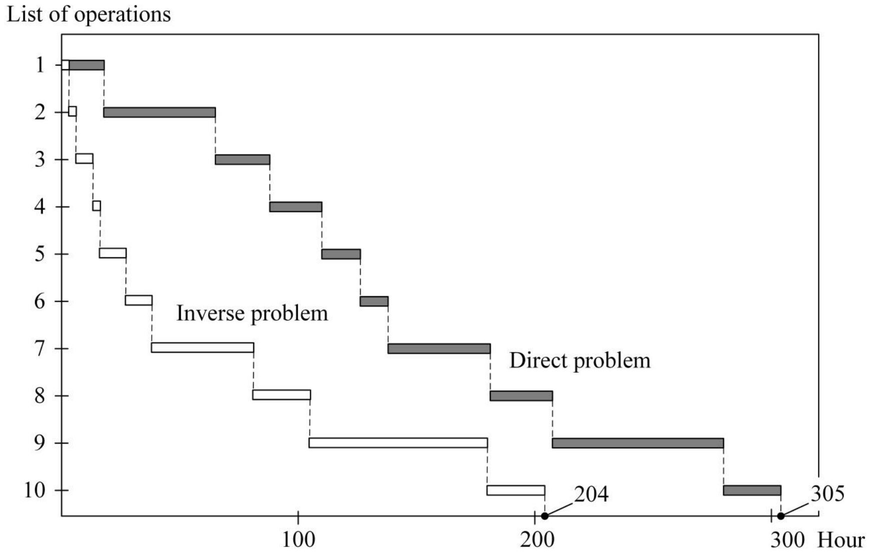

Fig. 3. Comparison of the calendar schedule of operation execution when solving the direct and inverse problems of shape formation

It should be noted that many manufacturing enterprises share the *TPM* and directly the production of *AO*, which justifies the opinion about the «little labor intensity of creating *DMU*».

In any case, the use of information in the form of *DMU* creates the possibility of solving a large number of tasks for the maintenance of shape-formation systems, the development of material and labor standards of *TPM*, the introduction of technological processes, the normalization and unification of technological equipment, and the modernization of equipment.

It should be noted that in the modern world, reengineering technology is successfully used in the manufacture of *AO*, which is confirmed by many publications, but there are practically no quantitative characteristics in the creation of *DMU*. At the same time, studies on the example of a helicopter stabilizer provide complete data on the impact of the reengineering method on the timing of *TPM*, data on the labor intensity of the reengineering process in solving shape-formation problems. A comparison of the labor intensity of solving the direct and inverse problems shows that the use of the reengineering method to reduce the time of *TPM* of a new AO does not produce a significant gain in time. This is explained by the fact that in the process of *TPM*, a large amount of design, technological, and organizational operations are carried out, which are interdependent and interrelated, therefore they require considerable time for their coordination and implementation. It should be borne in mind that the use of the reengineering method is very effective when launching a new article into production to perform quality control operations for individual operations, quality control of components and the article in general. Therefore, taking into consideration the analysis of the state of the issue according to the literature sources and our results on the example of the helicopter stabilizer, we shall present the main proposals and recommendations for reducing the time of *TPM* when applying reengineering:

1. Wide use of the reengineering method in solving inverse problems of *TPM*.
2. The use of the reengineering method in quality control of parts and articles for helicopter production.
3. The use of scanners in the repair and conversion of helicopters produced by *LTM* methods Improvement of organizational forms of *TPM* using reengineering.
4. Unification, standardization, and typification of technical and organizational solutions.
5. Testing structures for manufacturability in the process of design and technological preparation of production.
6. Information service to all performers.
7. Automation of design and technological projects.
8. Selection of the best scheme for assembling and linking procurement and assembly equipment using technical and economic analysis.

6. Discussion of results of studying the introduction of reengineering in the technical preparation of manufacturing of aviation technology

The scheme of linking homogeneous AOs obtained using *LTM* with *DMU* carriers when using reengineering (Fig. 2) has made it possible to obtain the results of assessing the labor intensity of creating *DMU* when solving direct and reverse problems for the helicopter stabilizer. Our calculations have established that the maximum labor intensity of the implementation of the inverse problem is from 194.78 to 213.22 man-hours (Table 1), and when implementing a direct problem – from 294.94 to 315.06 man-hours (Table 2). The results confirm the relevance of the introduction of modern engineering solutions, including reengineering, which is indicated in work [9]. Moreover, our studies will improve the effectiveness of the methodology reported in [9] by replacing the direct problem of shape formation with an inverse one.

Unlike [10] where the reduction in *TPM* terms is announced in the form of a statement without approbation, this work reports the results of calculations on the example of a helicopter stabilizer. A feature of the proposed calculations is the use of the well-known theoretical and probabilistic method (1) to (4), which gives a clear understanding of the timing of *TPM* and predicts the future labor intensity of technology. The results of the calculations for the helicopter stabilizer showed that when using reengineering technology, the difference in the labor intensity of TPM for the creation of AU differs by 1.5 times, and when creating *DMU* – by 3.7 times. Based on the proposed methodology, it can be recommended that the authors of work [10] perform the same calculations to obtain specific data on the feasibility of using pre-adjustment subroutines in CAM systems in order to reduce the time of TPM.

It is also necessary to take into consideration the complexity and limitations in the creation of *DMU* AU depending on the object under study, which is shown in detail in [11], which will affect the overall labor intensity.

The scheme of linking homogeneous AOs obtained by *LTM* with the analytical standard when applying reengineering combines a number of solutions based on it, namely:

– it makes it possible to create *DMU* and 3D models from a real object, as proposed in work [12];

– it solves the task of prototyping the part and shape-formation tooling, as reported in [13];

– it exercises control at all stages, both in the *TPM* and in the production of parts, the adequacy and reliability of which is confirmed by authors in articles [14, 15].

The use of 3D scanners and software to solve inverse problems in the industry can be recommended in the following cases:

– in the implementation of *AO* reengineering;

– to control the quality of *AO*;

– during the repair and conversion of *AT* produced by *LTM*;

– to digitize the manually created design layout of *AO* as a basis for further development;

– to detect, record, and identify undocumented changes in the manufacture of prototypes of products;

– for the manufacture of facsimile packaging for the finished transport product.

Confirmation of the adequacy and reliability of *DMU* will be a comparison of the portrait of the new *AO* with the portrait of the previously obtained carriers of the dimensions of *AO* parts.

The issues of reducing the duration of preparation of manufacturing of *AT* parts remain relevant in the scientific community, which is confirmed by the volume and results of the reviewed literature on this topic. Many authors suggest effective ways to achieve this result at different stages of *TPM*, approaching the issue from different perspectives, but the aspect of the impact of reengineering on this process remains poorly understood. Directly, the technology of reengineering is often considered in the key of reducing the labor intensity within the framework of a particular process, for example, at the stage of part control. However, its impact on *TPM* in general was not considered. We not only offer an effective way to introduce current technologies into the process of repair and modernization of an existing *AT* but also provide a specific calculation for reducing the terms of *TPM*, which is often avoided by the authors of other papers.

The simplicity of the proposed approach is in the application of the theoretical-probabilistic method. However, the reliability of the calculations obtained can be confirmed only by practical implementation when creating a new *AO*, repairing, or modernizing an existing *AO*. A single condition for achieving a minimum error in the calculations will be the initial correctness of the scheme for linking homogeneous articles using reengineering. The limitation of the proposed methodology will be the economic feasibility of using a 3D scanner and software for it. The introduction of reengineering technology will not only help reduce the time of TPM but will also allow the use of *TP* automation in the manufacture of *AO*s. The disadvantage of using reengineering technology at the stage of *TPM* will be the complexity of its implementation in the existing established production, which entails the consistency of direct and inverse problems of *AO* shape formation. It should be noted that the stage of introducing reengineering technology into the current system of an enterprise can be laborious but justified in terms of economic effect.

Therefore, our studies can be used to improve the existing technologies to produce *AT* and could become the basis for further research into other engineering objects.

7. Conclusions

1. A scheme for linking homogeneous *AO*s obtained by dependent linking methods with DMU when applying reengineering is proposed. The scheme connects and logically structures the capabilities of the reengineering technology and can be used to solve the tasks of prototyping parts, manufacturing molding equipment, control at all stages of production. Refining the scheme will increase the accuracy of the results of calculating the labor intensity of *TPM* when solving the direct and inverse problems of shape formation.

2. The proposed assessment of the labor intensity of work on the creation of DMU in solving the direct problem of shape formation by the theoretical-probabilistic method on the example of a helicopter stabilizer showed that the labor intensity is from 294.94 to 315.06 man-hours. The proposed assessment of the labor intensity of work on the creation of *DMU* in solving the inverse problem of shape formation by the theoretical-probabilistic method on the example of the helicopter stabilizer showed that the labor intensity is from 194.78 to 213.22 man-hours. The calculation results can be used as basic indicators for assessing the economic efficiency of production in general.

3. A comparative analysis of the labor intensity of creating *DMU* and the labor intensity of *TPM* in solving the direct and inverse problems of shape formation using reengineering on the example of a helicopter stabilizer made it possible to establish the following. The labor intensity of *TPM* in solving the direct and inverse problems for creating AU differs by 1.5 times, and when creating *DMU* – by 3.7 times. A feature of the proposed solution is the ability to use the well-known theoretical-probabilistic method in determining the labor intensity under real production conditions at *TPM AT*. Such results have made it possible to formulate proposals and recommendations to reduce the time of *TPM AT*.

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