Automation of scientific and technical expertise procedures in the methodology of technological audit of aircraft manufacturing

V V Kuritsyna, D N Kuritsyn, S M Shahrivar and S A Kazantsev
Institute of Aerospace High Technology and Production, Moscow Aviation Institute (National Research University), 4 Volokolamskoye shosse, Moscow 125993, Russia

Abstract. The work is devoted to issues of conceptual, informational and software problems of expert assessment of the current state, problems and development potentials of technological and production systems. The purpose of the research is to develop methods and tools for variative forecasting of operational characteristics of aircraft manufacturing facilities and automation of audit procedures for complex technological systems. The originality of this method is the use of the principles of technological inheritance of quality parameters of parts in the process of processing under the influence of technological energy and their relationship to performance characteristics. The advantage is the ability to define process controllers in the image of progressive technological operations of forming and modification of precision surfaces in order to ensure a guaranteed increase in operational efficiency by their flexible integration into production systems. A hierarchical model of the technological system implemented in the MatLAB Simulink visual modeling environment is proposed. The operation of the process controller is shown by the example of a diamond smoothing operation aimed at increasing the service life of precision friction pairs. The developed methods and tools are a tool for forming an evidence base for evaluating the technological potential, reliability, stability, and repeatability of technological processes in the total quality management system.

1. Introduction
The tasks of production quality management and ensuring the competitiveness of high-tech products are solved in a multidimensional space of objects, technologies, management tools. The field of aircraft construction, creation of transport equipment of new generation is the most difficult from the point of view of technological support [1].

The need to coordinate long-term strategic planning [2] and implementation in practice of specific mechanisms for the introduction and support of innovative technologies is noted in the state economic and political strategies of countries that determine the technical, economic and socio-political balance of the world [3, 4]. The scientific and technological knowledge and skills underlying expert forecasting become a strategic resource for the development of industrial sectors, national companies and incorporated corporations [5]. At any of these levels, it is extremely important to have information and be able to form ideas about the main directions of scientific and technological development in the medium and long term [6].

At the stages of the life cycle of complex science-intensive products of special engineering, including development, production, operation, it is often necessary to make decisions in conditions of insufficient
information, unclear algorithms for solving the problem, in conditions of risk [7]. The problem of adequate information support, accuracy and reliability of decisions in the scientific and technological sphere is now considered as one of the key.

Aircraft engineering products are complex technical systems, each component of which, in turn, represents a multi-dimensional production technological system for forming specific geometric shapes, physical and mechanical properties of parts under the influence, operational properties of components, reliability and performance of the product as a whole [8]. A particular difficulty in predicting and ensuring the required quality is caused by the huge number of influencing technological factors of technological operations and the inability to account for the synergistic effect of their influence through private analytical models.

At the same time, the accumulated experience of research, description and modeling of advanced technological methods for increasing the resource of high-loaded parts, such as surface-plastic deformation with a diamond tool, application of functional coatings, special chemical and thermal treatment, remains without analysis of the technological history of their formation, their joint influence, and mutual technological inheritance. Tools for describing the phenomena and effects of technological inheritance in production audit procedures are of considerable scientific and practical interest.

For the first time, the concept of technological inheritance in the field of mechanical engineering technology was proposed by Dr. A M Dal’sky, and advanced by scientists of the scientific school of the Bauman Moscow State Technical University [9-11]. In the field of aircraft engine production technology, the theory of technological inheritance was developed by the scientific school of Dr. L A Hvorostukhin of the Moscow Aircraft Technology University named by K E Tsio1kovsky [12] and his followers of the Moscow Aviation Institute (National Research University) [13].

Research and software solutions in the field of innovation management [14-16] offer mainly financial and economic models of investments and strategies, but do not take into account the technological risks of introducing new processing methods at the level of physical models. In the publishing space, the concept of financial, economic, and law audit of manufacturing and industries has long existed, while the concept of technological audit, proposed for the first time by Dr. A G Boitsov [1, 8], it is only now gaining strength, bringing to the forefront of analysis the mutual connection of physical phenomena and processes in the field of key technologies for forming and modifying surfaces.

Of particular importance in the field of mathematical representation of complex analytical networks, analysis of hierarchies, and decision-making are the works of Dr. S L Saati [17, 18]. This organizational approach and modern software tools for simulating MatLAB Simulink allow us to solve the problems of developing new methods and tools for technological audit procedures for aviation production.

The purpose of the research presented in this paper is to develop methods and software for variative forecasting of operational characteristics of objects manufactured in the environment of complex technological systems of aircraft manufacturing industries. The developed methods and tools are a tool for forming an evidence base for evaluating the technological potential, reliability, stability, and repeatability of technological processes in the universal quality management system. One of the main features of the analytical system being developed is the ability to search for and identify process controllers in order to ensure guaranteed operational efficiency by flexibly integrating advanced technological operations with precision surface modifications into production systems.

2. Technological audit decision extent
The analysis of areas of professional activity of objects, technologies and means of creation and operation of high-tech products, such as high-tech transport and space systems, allowed us to identify three vectors of space, reflecting the functional and support systems (figure 1): the object vector – the structure of an object segment transport systems, involving directly transport equipment, maintenance systems functioning in its structure management system (transport systems), it infrastructure deployment and maintenance; the technological vector – the structure of instrumental subsystems of complex objects maintenance at the stages of the life cycle, including technologies, methods and means of design, manufacture, operation of equipment and objects of transport systems; the control vector –
the structure of providing subsystems including methods and means of ensuring reliability, safety of objects and systems, management of innovative development, knowledge engineering, tools of economic and state regulation.

![Diagram of multidimensional structure of the entity-relationship model for industry segment information of the cluster.](image)

**Figure 1.** The multidimensional structure of the entity-relationship model for industry segment information of the cluster.

The composition of information for each vector is a hierarchical structure that can be detailed to the preferred level of analysis. It should be noted that if the object vector has individual specificity for each of the industry segments by means of transport, then, on the contrary, the other two vectors – technological and management tools – have similar composition and structure for any segment by means of transport and can be taken as typical.

When constructing the coordinate space "segment objects – life cycle technologies – management and regulation tools", a clear system of cells that meet the competencies of the cluster subject is determined.

Complex technical and technological systems have a very large number of parameters that reflect the design and functional perfection of the product (such as operating temperatures, pressures, speeds, as well as operational reliability, resource, durability, wear resistance, and so on). The creation of a product is determined by numerous indicators that reflect the perfection of manufacturing technologies, economic aspects of production, exploitation [19, 20]. Despite the numerous factors of the assessment tasks and under risk conditions, it is necessary to make scientifically-based decisions on which depend not only tactical moments, but also strategy of development of the enterprises, branch.

Nevertheless, in such conditions it is necessary to make scientifically grounded decisions on which depend not only tactical moments, but also strategy of development of the enterprises, branch.

The problem of technological support of operational properties of machine parts, and, consequently, and indicators of reliability of the product is solved at the present time due to the appropriate choice of processing conditions [1, 8]. Current trends in this direction are the study of the influence of the
processing conditions on the formation of the surface layer and based on operational properties of details of the status parameters of this layer, as well as in the calculation of the numerical values of these parameters and to ensure appropriate conditions of technological process of manufacturing of details [8, 10, 11, 20]. The surface quality of machine parts is determined by the combination of roughness and undulation characteristics, physical and chemical properties and microstructure of the surface layer. This variety of parameters reflects the complexity of the concept of "surface layer". These parameters currently form the basis for selecting a specific scheme of characteristics that are regulated in the design and technological documentation.

The urgency of solving the problem of ensuring the quality of technological processes with a sufficient probability of obtaining the required output parameters sets the task of developing a methodology for the integration of software and information systems of electronic support of production processes.

3. Methodological base
The development of the methodological base for modeling and evaluating advanced technologies is also dictated by the need to create and subsequent certification of quality assurance systems for products and its elements. The lack of a scientific approach in this case, as a rule, leads to irrational, energy-intensive methods of technological supply of parameters, requiring a large investment of time and labor, to increase the cost of manufactured parts without a proper increase in their reliability.

Technological audit serves as the basis for the development of design and technological measures and related documentation for implementation and implementation in production [2, 19]. Expert methods should be considered as one of the possible approaches to a comprehensive study of complex problems in which the final solution is not explicit. The expert method for assessing the effectiveness of technological solutions in the production of complex equipment is rationally used in cases where it is difficult to apply methods of objectively determining the values of complex integrated quality indicators due to their significant number, many relationships and regulators.

The methodology of technological inheritance is used to describe the mechanism of transferring product properties during the technological route of production. The concept of heredity, which originally arose in the field of analysis of the transfer of properties in biological organisms, is now beginning to enter such areas of knowledge as cybernetics, object-oriented programming, and system analysis. The development of methods of mathematical, structural-parametric, and functional analysis in relation to the production processes of high-tech engineering technology ensures the validity of this term. Technological inheritance is the phenomenon of transferring properties from previous manufacturing operations to the next; these properties can be both beneficial and negative. The scope of the term covers the stages of production and operation and is consistent with the ideology of product information support at all stages of the life cycle (CALS).

As a tool for a comprehensive description of complex phenomena arising in the process of forming precision parts and modifying their working surfaces, the most optimal use of matrix computing software MatLab (Math Works, Inc.) and the optional Simulink visual simulation extension package for modeling dynamic systems. The implementation of the principles of visual programming allows you to design models of complex structure and hierarchy. The researching of technological systems subject to random perturbations is carried out using statistical modeling and testing methods, experimental design techniques, statistical data treatment [21, 22].

4. Modeling the structure of the technological process
A technological system is a set of functionally interconnected elements of an enterprise’s production structure, technological equipment and performers performing technological processes of product manufacturing under regulated conditions in accordance with the requirements of regulatory and technological documentation. According to the concept of an electronic description of technical and technological systems, in the course of their life cycle, their models should be presented in a computer environment in the form of a hierarchy of information models that make up a single whole and have a
subordination, where each subsequent model is more detailed than the previous one and contains additional information.

A technological system, considered in time with discrete states of technological operations and transitions, is a tightly connected information network of a hereditary nature. The carrier of hereditary information is the actual surface of the part with a variety of parameters describing its condition.

The structure of the technological process can be represented in the form of a graph, which is based on an oriented elementary link that characterizes the conditions for a separate operation of the technological process while ensuring the considered parameter. A specific property of the workpiece, expressed by the input characteristic of the link \( X_{v(p-1)} \), changes during the technological operation in accordance with the transmission coefficient of the hereditary relationship \( K \) for this operation and is characterized by a new value \( X_{vp} \): 

\[
X_{vp} = f \left( K_{(p-1)p}, X_{v(p-1)} \right)
\]

These changes are determined by the action of a set of technological factors \( \{t_1, t_2, \ldots\} \) for each operation of the technological process (figure 2).

![Figure 2. Concept model of a link of a technological system (operation): \( p \) – the observable operation number; \( v \) – the observable parameter number; \( j \) – some number of some influencing parameter (if there is a transverse connection); \( i \) – some number from previous operations.](image)

From the point of view of system analysis, the technological operation is presented in the form of a “black box”, the input of which contains the following information signals: 1) the value of the investigated surface quality parameter before processing in this operation; 2) technological parameters (processing modes, tool characteristics, etc.); 3) random environmental factors that may affect the output characteristic (interference). At the output of the SUB-system, we obtain the analyzed output characteristic, which is the value of the investigated surface quality parameter after processing in this operation.

With a complex manifestation of technological inheritance, correlations of heterogeneous parameters of the surface layer are traced, such as, for example, the effect of residual stresses on the geometry of
the product. The so-called transverse hereditary bonds are formed. In the general case, the technological process is penetrated by hereditary bonds of longitudinal and transverse species (figure 3) [2, 13].

A comprehensive assessment of the manifestation of technological inheritance can be represented by the subsystem of the integral characteristics of technological inheritance (figure 4), where the transmission coefficients of hereditary relationships ($K$) are presented as weighting factors for the quality indicators of the part ($X$) formed during the operations of the technological process:

$$X_{vp} = \frac{1}{K_{v(p-1)p}} \cdot X_{v(p-1)} + \frac{1}{K_{vp}} \cdot X_v + \frac{1}{K_{vipj}} \cdot X_{ji}.$$  (1)

**Figure 3.** Implementation of a simulation model of technological inheritance in MatLab Simulink.

**Figure 4.** Subsystem of complex hereditary relations of the generalized form.

The mathematical model of the general form of technological inheritance is very multidimensional:

$$X_{vp} = \sum_{j=1}^{p-1} \left[ \sum_{i=0}^{p-1} \left( \frac{1}{K_{vipj}} \right) X_{ji} \right].$$  (2)
where $X_{vp}$ – observable of $v$-th detail parameter quality after $p$-th process operation; $v$ – the number of the observable parameter of the quality of the part (workpiece); $p$ – the number of the observable technological operation; $i$ – the number in the sequence of technological operations from the beginning of the process to the operation under consideration ($i = 0, 1, \ldots, p$); $j$ – current number from the number taken into account ($j = 1, 2, \ldots, s$) basic geometrical and physico-mechanical parameters.

When forming each of the links of the complex model of technological inheritance, it is possible to use both one method and different ways of describing transfer mechanisms. The coefficients of transmission of hereditary connections ($K$) have one of the following types:

- linear heredity coefficients ($K = \text{const}$);
- analytical dependencies, functional relationships with initial parameters, technological modes of operation, and environmental factors $K = f(X_y, t_y, S_y)$;
- regression models of various degrees indicating weight estimates of the influence of initial characteristics, technological factors, and their combined influence $K = f(X_y, t_y, S_y, \beta_{xy})$;
- stochastic dependencies, statistical relationships with the characteristics of mathematical expectation, variance, etc.

The source of information about the type and particular analytical expressions of the coefficient of transmission of hereditary connections are determined by one of the following methods:

- experimental research in the subject area of material processing technology with statistical processing of experimental data;
- from published sources of research results, dissertations in the subject area;
- predicting the expected dependencies from the acceptable range for both standard situations and the risk zone.

When studying the process of property formation, a technological operation should be selected as the structural unit of the process. It is necessary to use special models that characterize the contribution of individual mechanisms in the formation of the value of a particular parameter of the quality of the part. When building individual links of the technological system, it is possible to consider them both locally, without connection with other operations of the technological process with the interruption of external links, and comprehensively, in conjunction with other elements of the system.

The model of technological inheritance of a real technological process is a subset of the general model, which includes only significant relationships of a hereditary nature. A description of the process of technological inheritance using a system of equations facilitates the task of quantifying properties. The number of variables included in its full description at the stage of analysis determines the scale of the object.

The simulation model of the technological system in the environment of MatLab Simulink is built using the folding mechanism of the structure, and each transmission link of the hereditary connection, in turn, can be a subsystem determined on the basis of scientific research, statistical analysis, technological audit and expert evaluations. The simulated object (technological system) is represented graphically by its functional parametric block diagram, which includes blocks of system elements and communication between them. In terms of Simulink, such a block diagram is referred to as the S-model. Thus, figure 3 presents a simulation model of a technological system for ensuring the quality of the surface layer of parts using the example of manufacturing a hydraulic cylinder body of a precision pneumatic-hydraulic system, implemented using the MatLab Simulink visual simulation system using drag-and-drop technology. The functional blocks of the elements of the simulated system can, in turn, be nested subsystems with their organization, forming hierarchical structures. Subsystems, the structure of which during modeling can be either visually hidden or expanded if necessary, decomposition and detailed analysis, in the terminology of Simulink are referred to as SUB systems (SUB system).

An example of a model of a subsystem of a technological operation for diamond smoothing is presented on the figure 5. Diamond smoothing refers to methods of surface plastic deformation processing and plays a special role in shaping the quality and performance properties of parts [12, 23].
The use of diamond smoothing at the final stages of the technological process allows you to multiply the bearing capacity of the surface and the resource of friction units, by increasing the surface hardness, reducing roughness, and distributing residual mechanical stresses in the surface layer [24]. The result of the technological operation depends on such modes as kinematic scheme, feed, processing speed, tool clamping forces, material and geometry of the tool, etc.

![Hierarchical modeling in the refinement of technological systems.](image)

Figure 5. Hierarchical modeling in the refinement of technological systems.

The principle of visual modeling of a link in a technological system is shown by the example of the formation of surface roughness ($R_a$) when smoothed with a diamond indenter. The longitudinal and transverse roughness, the degree and depth of hardening of the machined surface depend on the initial roughness ($R_{a\ previous}$) of the part, the pressing force ($P_y$) and the radius of the sphere ($R_{sph}$) of the diamond indenter. Reducing the initial roughness before processing reduces the value $R_a$ after processing. The value of the speed during processing slightly affects the value $R_a$. The feed has the greatest effect on the resulting surface quality, on the one hand, in the case of a small feed, each surface point undergoes deformation several times, on the other hand, a small feed reduces the processing productivity, an increase of 1.1–1.2 times leads to an increase in roughness by 1.5–2.0 times. After processing with optimal conditions, there is a relation, was the basis of the model of the transmission link of the technological system:
\[ R_a = K \cdot R_{a \text{previous}} , \text{ where } K = f \left( t, R_{a \text{previous}} \right), \text{ thus } R_a = \frac{110 \cdot s^2}{R_{sph}^2} \cdot R_{a \text{previous}} \]  

where \( t \) – vector process parameters, such as feed per revolution (s), tool radius (R_{sph}).

The tools of the simulation environment allow the seamless integration of S models into the overall system, using the principle of folding the structure. In this case, it is possible to embed subsystems of individual links of a technological system without affecting its general structure, or with minimal transformations of complex longitudinal and transverse connections.

The MatLAB S-model is implemented as an example of the method of technological audit of production of precision pneumatic hydraulic system parts. The dimension of the model is \((9 \times 9 \times 9)\) (9 positions of the observed technological operations; 9 positions of the observed parameters of the surface layer; from 3 to 9 dynamically varying technological parameters and conditions of individual operations). To study the effect of processing conditions, the following limits of variation were selected: Feed per revolution \( s = 0.02-2 \text{ mm/rev}, R_{a \text{previous}} = 0.64-8 \mu \text{m}, R_{sph} = 1-4 \text{ mm}, P_y = 120-300 \text{ N.}\)

Connecting to the system of simulation of the random effect (the signal source as a random number generator of the normal distribution law) allowed us to confirm the technological stability of the operation.

The effectiveness of embedding the diamond smoothing operation in the technological process of obtaining precision holes of pneumatic cylinders as a regulator of technological inheritance of such parameters as hardness, roughness, and residual stresses was shown by subsequent production testing. Full-scale products have shown that diamond smoothing is the most suitable method of surface-plastic deformation for processing surfaces of hard metals and coatings [23, 25]. This is due to the high hardness of the diamond and the specific conditions of its contact interaction with the doped layer, which results in plastic deformation of the hardest deposited materials.

The synergistic effect of the combined effect of coating and diamond smoothing operations provides broad prospects for combined processing in order to increase the resource and reliability of critical tribotechnical units of aircraft. The new technology of combined hardening is based on a combination of electroerosive hardening and diamond smoothing with the creation of the effect of surface reinforcement and the creation of special regular microreliefs.

Progressive methods of exposure to concentrated energy flows of various nature, such as surface plastic deformation [25], electrospark alloying [26], combined methods of hardening and shaping [23, 26] are considered as powerful control links in the technological chain of ensuring operational properties of critical parts and assemblies aviation technology.

5. Technological expertise in making production decisions
In practice, the implementation of technological systems for shaping and modifying surfaces is a multivariate creative task under fuzzy conditions and a lack of information [13]. Alternative technological methods have both advantages and disadvantages. Therefore, it is not always obvious which method is optimal for use in a particular technological process. Making a decision in this case is an action on a multitude of alternatives, which results in a subset or a single selected option. In the conditions of a limited resource of time and means for making technological decisions, an effective tool is the use of automated systems for supporting the adoption of technical decisions based on multivariate and multicriteria optimization algorithms, mathematical statistics, and processing of expert opinions.

The evaluation criterion when choosing a solution is a system parameter that reflects a weighted set of features by which a single solution can be distinguished from many alternative ones. An array of assessment criteria is a subset of the full array of parameters of a technical (technological) system selected according to the purpose of the assessment. The classification of criteria is similar to the classification of parameters of technical systems [2] and includes groups of indicators reflecting the degree of perfection of the product design, its operability, production and operational manufacturability;
the degree of perfection of the production system; commercial, environmental, social and other indicators.

Integral assessment of technological alternatives by criteria includes the following steps: establishing for each option the degree of satisfaction (fulfillment, quality) of requirements for each criterion \( F_{jm} \); calculation of the relative quality indicator of the compared options for each criterion \( f'_{jm} = F_{jm} \cdot q'_j \) of the criterion \( m \), taking into account the significance (importance) of the criterion \( (q'_j) \); calculation of a complex (integral) quality indicator of each option as the sum of local estimates taking into account the weight contribution of the significance of the criteria: \( Q_f = \sum_j f'_{jm} \); generalization of opinions received from each expert, taking into account qualification factors and the significance of the members of the expert group. The conclusion of the technological expertise is formed with the calculation and indication of quality according to the parameters of consistency, accuracy and reliability.

Based on the results of calculating the eigenvectors of the priority matrix of influence on the failure-free operation of precision pneumatic hydro units, the weight of the influence of technological operations was shown (in normalized estimates):

- honing and superfinishing of cylindrical surfaces \(-0.3\);
- surface hardening with a diamond tool \(-0.25\);
- application of special wear-resistant coatings \(-0.25\);
- other operations (summary) \(-0.2\);

and weight of influence of surface layer parameters:

- geometric accuracy \(-0.29\);
- roughness \(-0.26\);
- surface hardness \(-0.25\);
- other parameters (summary) \(-0.21\).

The infological data model when implementing information processes for processing expert assessments in multivariate and multicriteria problems represents a multidimensional matrix structure. The software implementation of the automated system organically lays on the combination of the methods of relational (tabular) data representation in Excel and information representation of hierarchical networks in MatLAB [13].

The advantages of the software implementation of the developed automated system of technological expertise include: automation of statistical calculations; prompt response to a change in production conditions, objects and subjects of analysis; the ability to forecast development options and the consequences and risks of the adoption of various innovative decisions and projects; modular structure, flexibility and the possibility of modification with the aim of further expanding the range of tasks; visualization and interactive dialogue support [13, 19]. Modern information technologies provide an opportunity for modeling processes, operational analysis, preparation and presentation of results for subsequent decision-making.

6. Conclusion

As a result of research, a methodology has been developed and tools for variative forecasting of operational characteristics of aircraft manufacturing facilities and automation of audit procedures for complex technological systems have been proposed.

The novelty of this method is the use of the principles of technological inheritance of quality parameters of parts in the process of processing under the influence of technological energy and their relationship to performance characteristics.

A hierarchical model of the technological system implemented in the MatLAB Simulink visual modeling environment is proposed. Technological regulators are defined in the image of progressive technological operations of forming and modifications of precision surfaces aimed at increasing the resource of precision friction units. Establishing patterns of technological inheritance can improve the
reliability of technological systems by using special technologies as a regulatory link in the technological chain.

A model of a technological system built using an integrated technique is a dynamically updated structure and allows us to analyze the effectiveness of technological support both in individual operations and in the technological process as a whole. When constructing the individual links of the technological system, it seems possible to consider them both locally, without communication with other operations of the technological process with interruption of external connections, and comprehensively in conjunction with other elements of the system.

The integration of one of the fastest matrix mathematical systems - MatLab - with the Simulink simulation package opens up new possibilities for using the most advanced mathematical methods to solve the problems of dynamic and situational modeling of complex technological systems. MatLab Simulink has the ability to organize simulation models of dynamic systems, analyze their functioning and evaluate the output characteristics of processes. The modular construction principle and intuitive interface provide dynamic model management, structure editing and the addition of functional modules to the model.

The development of automated means of monitoring and control of the system of parameters of the state of the surface layer during the technological process, using the laws of technological inheritance, allows you to dynamically combine the experimental results of the study of methods of technological support of operational properties and computer-aided design of technological processes, which makes it possible to analyze many options for technical solutions to increase reliability results coding, forecasting and management.

Tools for processing expert assessments in multidimensional and multi-criteria tasks can improve the efficiency and effectiveness of technological management of industrial enterprises.

References

[1] Eliseev Yu S, Boytsov A G, Krymov V V, Hvorostukhin L A 2003 Production technology of aircraft gas turbine engines (Moscow: Mashinostroyeniye) p 512

[2] Siluyanova M V, Kuritsyna V V and Boitsov A G 2017 Models and Methods of Technological Audit of Hi-Tech Industries (Moscow: Mosk. Aviats. Inst.) p 160

[3] Morgunov Yu A, Panov D V, Saushkin B P and Saushkin S B 2014 Advanced Technologies in Machine Engineering Industry: Physical-Chemical Methods and Technologies (Moscow: Forum) p 928

[4] Morgunov Y A, Saushkin B P and Shandrov B V 2016 Development of conceptual equipment of engineering technology. *Sprav. Inzh. Zh. Prilozh.* 4(229) 3 doi: 10.14489/hb.2016.04.pp.003-007

[5] Isachenko V A, Astakhov Yu P and Saushkin B P 2016 Aerospace engineering technology: problems and prospects. *Journal "Tekhnologiya Mashinostroeniya"* 1 10 [in Russian]

[6] Morgunov Y A, Saushkin B P and Shandrov B V 2019 Knowledge intensity if engineering production and its elements. *Science Intensive Technologies in Mechanical Engineering* 6(96) 37 doi: 10.30987/article_5ce675a22352c.1.74868398

[7] Kraev V M, Siluyanova M V and Tikhonov A I 2019 Assessment and improvement of rationality methods of modern aircraft engines design and technological solution. *Journal of Physics: Conference Series* 1353(1) 012033 doi: 10.1088/1742-6596/1353/1/012033

[8] Boitsov A G, Kovalev A P and Novikov A S 2007 Mechanical and Physicochemical Processing in Production of Aircraft Engines (Moscow: The Bauman Moscow State Technical University) p 584

[9] Dal’sky A M, Bazrov B M and Vasilyev A S 2000 Technological heredity in machine-building production (Moscow: Mosk. Aviats. Inst.) p 364

[10] Bazrov B M, Rodionova N A 2019 Reconciling Quality Requirements over the Product Life Cycle. *Russ. Engin. Res.* 39 407 https://doi.org/10.3103/S1068798X19050058

[11] Vasilyev A S, Yamnukov A S, Matveev I A, Yamnikova O A 2019 Influence of hereditary technological errors of production of a basic pipe on parameters of the assembled propulsion
section. *Chernye Metally* 1 67

[12] Khvorostukhin L A, Shishkin S V, Kovalev A P and Ishmakov R A 1988 *Increase of the Bearing Capacity of Machine Parts by Surface Hardening* (Moscow: Mashinostroenie) p 144

[13] Siluyanova M V and Kuritsyna V V 2018 Automated management in aerospace production. *Russ. Eng. Res.* 38(3) 201 doi: 10.3103/S1068798X18030085

[14] Pausits A 2019 Innovation Audit: Measuring Innovation Management Capabilities. In: Carayannis E. (eds) *Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship*. (Springer, New York) https://doi.org/10.1007/978-1-4614-6614-1

[15] Bross U, Inzelt A, Reib T 1998 Principles of Technology Audit. In: Bio-Technology Audit in Hungary. Technology, Innovation and Policy (Series of the Fraunhofer Institute for Systems and Innovation Research) *Physica, Heidelberg* vol 7 https://doi.org/10.1007/978-3-642-52472-1_4

[16] Grigor’ev S N, Dolgov V A, Krasnov A V and Andreev N S 2015 A method of technologic audit of technical re-equipment projects in aircraft production enterprises. *Russ. Aeronaut.* 58 244 https://doi.org/10.3103/S106879981502018X

[17] Saaty T L and Vargas L G 2012 The possibility of group choice: pairwise comparisons and merging functions. *Soc Choice Welf* 38 481 https://doi.org/10.1007/s00355-011-0541-6

[18] Saaty T L 2016 The Analytic Hierarchy and Analytic Network Processes for the Measurement of Intangible Criteria and for Decision-Making. In: Greco S, Ehrgott M, Figueira J (eds) *Multiple Criteria Decision Analysis. International Series in Operations Research & Management Science*, (Springer, New York) 233 https://doi.org/10.1007/978-1-4939-3094-4_10

[19] Siluyanova M V, Kuritsyna V V and Iosifov P A 2016 *Strategies, Methods, and Models of Technological Development of Aerospace Industry* (Moscow: Mosk. Aviats. Inst.) p 160

[20] Kondakov A I and Vasiljev A S 2018 Evaluation of the types of multiproduct manufacturing of machine components and some aspects of their design. *MATEC Web Conf.* 224 01121 doi: 10.1051/matecconf/201822401121

[21] Schenk H Jr 1979 *Theory of engineering experimentation. 3rd Revised edition* (Washington New York London: Hemisphere McGraw-Hill) p 320

[22] Orlov A I 2020 Organizational and economic modeling in the organization of production in the epoch of digital economy. *MATEC Web of Conferences* 311 02001 https://doi.org/10.1051/matecconf/202031102001

[23] Boitsov A G, Mashkov V N, Smolentsev V A and Khvorostukhin L A 1991 *Surface Hardening of the Parts by Combined Methods* (Moscow: Mashinostroenie) p 144

[24] Shishkin S V 2019 Application of finish-strengthening process with diamond smoothing for bearing capacity increase of joints with tightness. *Bulletin of Bryansk State Technical University* 6(79) 4 doi: 10.30987/article_5d10851eda9a19.64369355

[25] Kuritsyna V V, Siluyanova M V and Kuritsyn DN. et al. 2020 Local Surface Deformation of Precision Airplane-Engine Components. *Russ. Engin. Res.* 40 266 doi: 10.3103/S1068798X20030144

[26] Denisov L V, Boitsov A G and Siluyanova M V 2018 Surface hardening in hydraulic cylinders for airplane engines. *Russ. Eng. Res.* 38(12) 1080 doi: 10.3103/S1068798X18120237