Probabilistic Modeling for Manufacturing of Automotive Electric Equipment

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Research Article

Keywords: quality criterion, probabilistic estimation, MATLAB, quality index, Monte Carlo method

Posted Date: March 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-247431/v1

PROBABILISTIC MODELING FOR MANUFACTURING OF AUTOMOTIVE ELECTRIC EQUIPMENT

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Abstract

A generalized quality criterion is proposed for the processes of designing and manufacturing electrical equipment. The relationship between the parameters of the technological process of manufacturing electrical equipment and the ones of statistical plans acceptance quality control is taking into account for the calculation of the criterion. This creates the prerequisites for effective management of design and manufacturing processes to achieve the desired level of quality.

Keywords: quality criterion; probabilistic estimation; MATLAB; quality index; Monte Carlo method

1. Introduction

The quality of the parts manufacturing depends on the huge number of the parameters, i.e. quality of the equipment, the accuracy of the technological carts, materials used for production, etc. A little deviation of the parameter values leads to changes in the parts parameters and production defects. Such parts are removed from the manufacturing process. This leads to worsening in the economical criteria and, as a result, to the loss of profit. The situation is getting tougher.

On the other hand, there are practically no parts that are used separately. In most of the cases, the parts are included in the whole system/aggregate, where they work all together.

The use of special arrangements allows combining parts of the whole system in which parameters can be out of the production limits but these parts combination is in the range of the system quality.

For the implementation of that idea, the probabilistic model of distribution of the dimensional parameter is offered. The model workability is estimated on the example of the active zone of the electromechanical converter in the tolerance field established by the technical conditions.

2. Materials and Methods

We used the basic principles of probability theory to develop our algorithm. For modeling, the MATLAB software package was used.

2.1. Simulation modeling in product manufacturing management.

This methodology helps to improve the quality of products at the design and production stages while reducing the time and cost of work. The effectiveness of simulation is based on the fact that it uses a priori, that is, pre-experimental research mechanisms that fully replace expensive experimental work with computer modeling. It should be noted that simulation modeling can be effectively used to solve quality management tasks at the design and production stages in those cases when:

- the development and production are carried out in a certain sequence from the preparation of the technical assignment to the consideration of the requirements of consumers;
- the quality of execution of each stage of the processes under consideration can be described by the requirements imposed on its input, the processes themselves and the output;
- criteria for the quality of the input, process, and output parameters have been established. The process of creating products is one of the most complex and difficult for modeling. This is due to the fact that it consists of a large number of stages, operations and other acts of transition from less perfect and completed to more specific and complete. Each stage of the process can differ from the previous and the subsequent in form and content; it can have different duration and be performed at different enterprises or divisions of one enterprise and so on.

When drawing up a model, one should be guided by the sequence of tasks to be solved, as well as by the consistency of posing questions and obtaining answers within the framework of the system approach. However, one should bear in mind that the process control system cannot be described by one simple model. A set of models is needed that reflect the various stages of the processes [1].

The process of creating products can be represented in the form of a diagram (figure 1). The technical requirements developed on the basis of market research and enterprise policy in the field of quality are

input parameters of the design process, and its output parameters serve as inputs to production processes. This sequence is inherent in the creation of both complex products and simple ones.

In the block (6), the technical requirements are compared with the design results and the obtained quality indicators of the finished product. This integrated model allows monitoring the input, process, and output, and also allows determining the extent of the impact of the input and process on the result. According to the received data, decisions are made on the development and application of corrective actions [2].

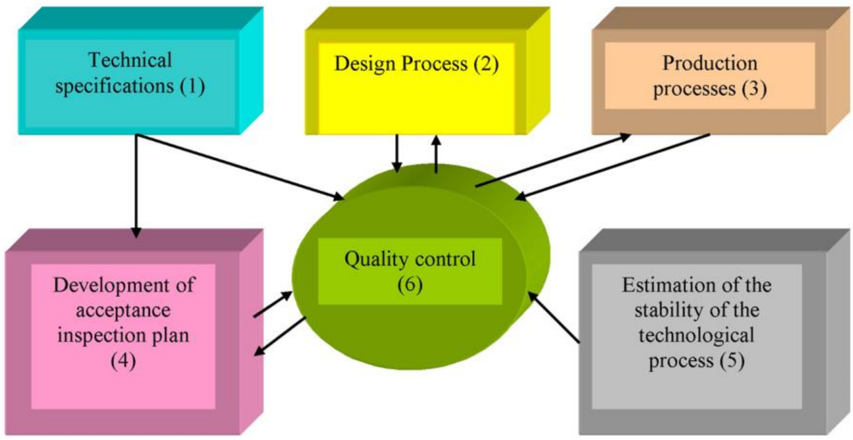

Fig. 1 The process of creating a product

At the design stage, a system of relationships between material properties and dimensional relationships is established and, what are especially important, methods are laid for achieving product quality, taking into account the most economical method of production under the planned production program. At the production stage, more complex tasks of materializing communications are solved by controlling technological processes and operations. An adequate description of the processes is possible using a procedure called modeling. Modeling is the process of creating an accurate and convenient for the perception and analysis of the description of the system as a set of interacting components and the relationships between them.

The task of improving the quality and reliability of the products of the main group should be considered in the context of the interaction of the design and production stages. Right here, the basics of the product are laid, the evaluation of which can be made only if the influence of the processes of the formation of

quality indicators and parameters of the quality management system is known. As it was shown, the technological spreads of the main group of the sizes of the active zone of electromechanical converters (EC) have a significant effect on the performance characteristics of the device in which it belongs. Hence increasing the stability of the electromagnetic characteristics of the EC will help improve the quality and reliability of the car.

The stability of the operating characteristics of the generator, the electric starter, the motor - reducer of the electric window, the electromechanical power steering and the starter generator depend directly on the stability of the technological process of manufacturing the elements and the structure as a whole [3,4].

2.2. Modeling of the generalized quality index

To create an integrated computer model that provides description and interaction of design, production and quality management processes, it is necessary to create fundamentally new structures that combine elements of mathematics, probability theory, mathematical statistics and logic [5]. A link between them should be a single indicator that can reflect the characteristics of the quality (stability) of the technological process of manufacturing EC. The structure of the system reflecting the relationship between individual stages of research and the construction of an effective quality management system for the design and production of technical devices on the basis of a single indicator is presented in Figure 2.

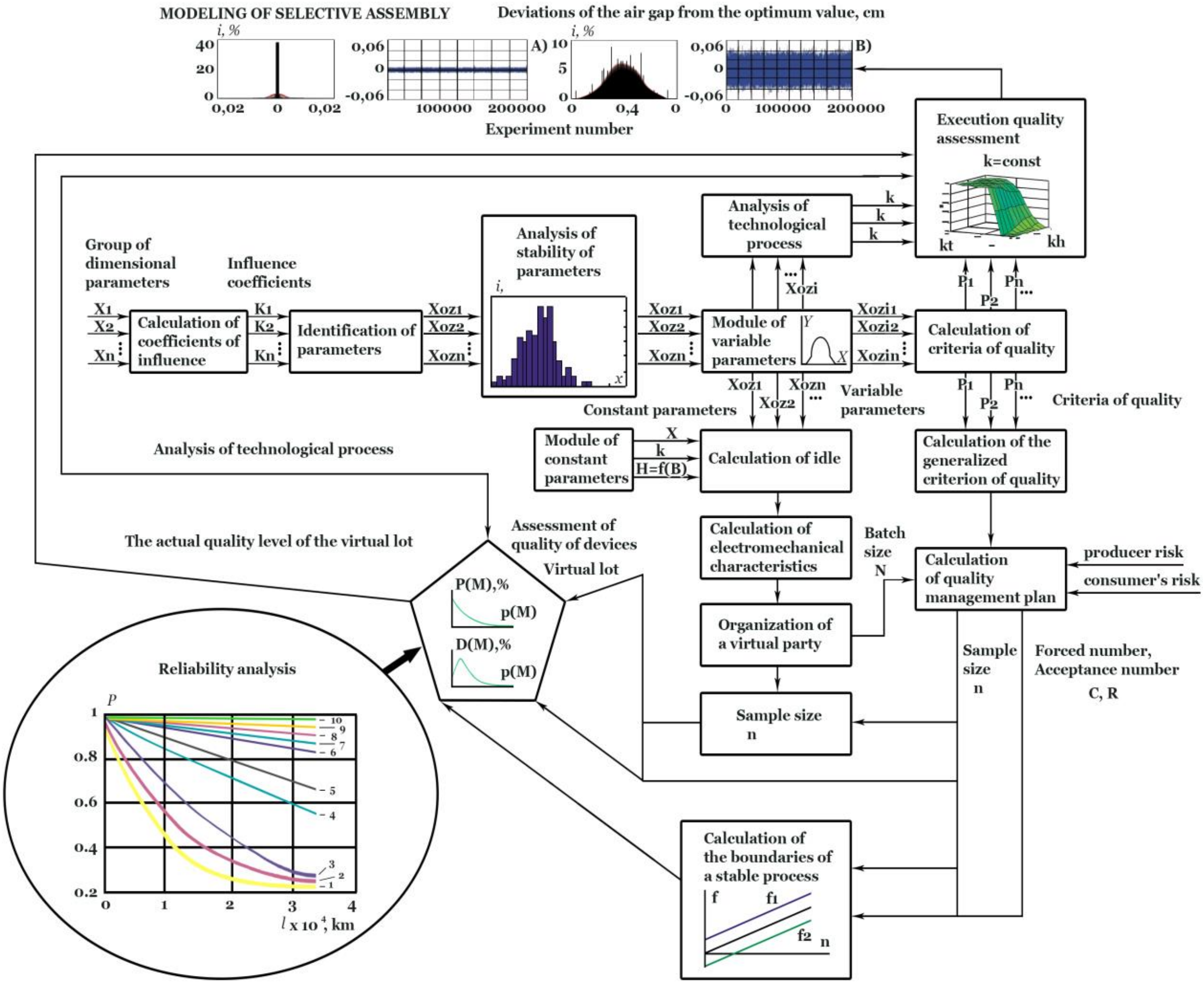

Fig. 2 The structure of the integrated model

Here, the object of research is the technological process of manufacturing the main group of dimensional parameters of the EC, presented in the form of a mathematical relationship between the input and the output parameters of the main group devices (generator set, electric starter, Tel steering, electric window motor-reducer, the starter-generator set. The formation of the scatter of key sizes of the active zone of the EC is carried out with the help of a random number generator (Fig.3).

In the model (Fig. 2), a virtual batch of electrical products is organized using a statistical method for predicting the behavior of a complex system (the Monte Carlo method). The connection between the input and output parameters is carried out on the basis of the technique for calculating the technical characteristics of the generator, starter, motor gear, power window, electromechanical power steering and the starter generator [6].

As a generalized criterion of quality (stability) of the technological process for manufacturing devices, a probabilistic estimation of the hit of the key dimension parameter within the limits of the established TU tolerance field is considered. When determining the quality criterion, it is assumed that the errors in the manufacture of parts within the tolerance are distributed according to the normal law [7–10]. Consequently, the probability of getting the parameter in question in the tolerance field (P_i), taking into account the estimate of the standard deviation, is calculated by the formula:

$$P_i = \frac{1}{\sigma\sqrt{2\pi}} \int_{x_l}^{x_u} e^{-\frac{(x-x_{avg})^2}{2\sigma^2}} dx \,, \qquad (1)$$

Where σ – is the standard deviation of the size;

x_{avg} – the average value of the size within the tolerance;

x_l, x_u – lower and upper value of tolerance limits;

π – a mathematical constant.

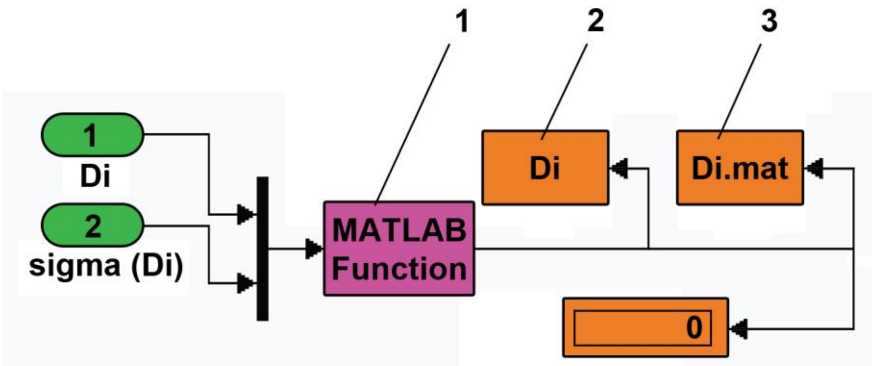

Fig. 3 The organization of the random number generator in the model describing the technological process of production of the basic elements of electrical equipment.

Where:

1 – random number generator;

2 – the block of record in the working window of the program;

3 – block writing to the program file.

Since any electromechanical converter consists of components, each of which determines its quality, then the average value of the quality criterion of the technological process can be represented in the following form:

$$P_{avg} = \prod_{i=1}^{m} P_i \quad , \tag{2}$$

Based on the obtained value of the quality factor of the technological process of manufacturing devices, it is possible to determine the possible average (d_{avg}) number of defective products in a batch expressed as a percentage:

$$d_{avg} = (N - P_{avg} \cdot N) \cdot 100\% , \tag{3}$$

where N is the volume of the controlled lot.

Table 1 presents the values of the key size parameters for the input of the quality management models for the generator, the electric starter, the motor reducer of the electric elevator of the electromechanical power steering amplifier and the starter generator, and also their geometric tolerance fields.

Individual design values and generalized indicator of the quality of the technological process for manufacturing the technical devices of the main group, according to the parameters studied, are presented in Table 2.

The analysis of the obtained data (Table 2) shows that the individual values of the quality indicators for each of the key sizes of the core take the same values of 0.9973.

This circumstance can be explained by two factors: the first is the probabilistic nature of the quality index, i.e. the evaluation of quality is the probability of manufacturing a dimensional parameter within the geometric tolerance field, and the second is that the same approaches apply to assign the boundaries of the tolerance field to a geometric size.

Thus, the complexity of the quality management system directly depends on the number of input key production parameters.

The constructed computer model of a batch of technical devices of a given volume provides an opportunity for a full and objective study of the influence of the technological process of manufacturing a key group of dimensional parameters on electromagnetic characteristics [11]. The objectivity of the model follows from the fact that in virtual structures we took into account the elements of randomness operating in the actual production process.

The generalized indicator of the quality of the technological process for the manufacture of technical devices creates the prerequisites for the design and optimization of statistical methods for acceptance control of the quality of the tested batches of products, based on the existing level of quality [12].

3. Investigation of the quality indicators of the technological process.

Mathematical modeling of the quality indicators of the technological process provides for the use of input parameters of the characteristics of the virtual batch of technical devices.

Outputs – accuracy factors k_t, attitude k_n, stability k_c of the technological process. Here carried out the analysis of the relationship of the output parameters with the generalized indicator of the quality P:

$$k_t = \frac{6 \cdot S}{\delta}; \tag{4}$$

$$k_n = \frac{\overline{X} - x_{avg}}{\delta}; \tag{5}$$

$$k_c = \frac{S_{t_1}}{S_{t_2}}. \tag{6}$$

Where $\overline{X}$, is the sample arithmetic mean for the given size; S is the sample standard deviation; δ – tolerance parameter; and S_{t_1}, S_{t_2} – average quadratic deviation at time moments t_1, t_2. It should be noted that there are special conditions for choosing t_1, t_2. The time moments t_1 and t_2 characterize the technological cycles, which are carried out strictly one after another. The determination of the sample values of the arithmetic means the standard deviation for a given geometric size is a random sample from the virtual batch (module evaluation of process parameters Figure 4) [13,14].

The calculated values of the coefficients for each of the considered geometric size are presented in table 3.

Together with the analytical drawing of the quality of the technological process of production of EC, it is necessary to assess the influence of the accuracy, mood, and stability on the generalized quality index R. To do this, from the expression determining the coefficient of accuracy, we derive the sample mean square deviation:

$$S = \frac{k_t \cdot \delta}{6} \tag{7}$$

From the expression defining the coefficient of mood, we define the coordinate of the middle of the tolerance field:

$$x_{mid} = -k_n \cdot \delta + \overline{X} \tag{8}$$

Define the sample mean square deviation at time t_2 through the stability factor:

$$S_{t_2} = \frac{S_{t_1}}{k_c} \tag{9}$$

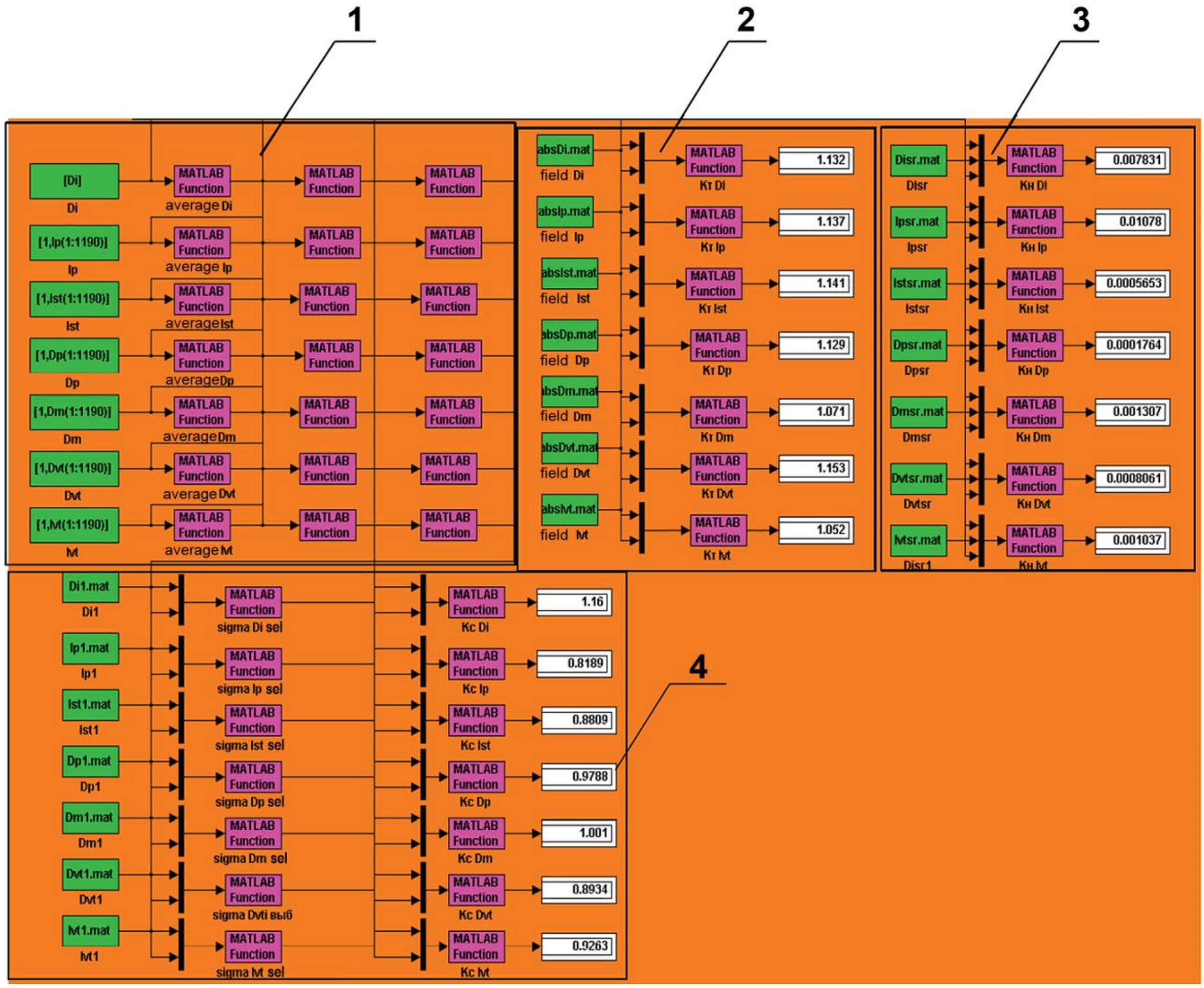

Fig. 4 Steady technological process parameter estimation module

A generalized criterion for the quality of the technological process will be determined for the time instant t_2. We obtain a formula for calculating the generalized criterion for the quality of the technological process:

$$P_i(t_2) = \frac{1}{\dfrac{\left(\dfrac{k_t \cdot \delta}{6}\right)_{t_1}}{k_c} \cdot \sqrt{2 \cdot \pi}} \cdot \int_{x_l}^{x_u} e^{-\frac{\left(x - \left(-k_n \cdot \delta + \overline{X}\right)\right)^2}{2 \cdot \left(\frac{\left(\frac{k_t \cdot \delta}{6}\right)_{t_1}}{k_c}\right)^2}} \cdot dx \qquad (10)$$

For an ideal technological process:

$k_t = 1$; $k_n = 0$; $k_c = 1$; $P_i(t_2) = P_i(t_1) = P_i = 1$

Changing the values of the coefficients of accuracy, stability, and mood from 0 to 1, we make an example and calculation of the characteristics of the starter generator reflecting the dependence $P=f\ (k_t, k_n, k_c)$ for the outer diameter of the armature and the inner diameter of the stator (Figures 5 – 7).

For $k_c = 0.1$ we get an unstable technological process, the generalized quality criterion approaches unity only when $k_n = 0$, and $k_t = 1$ (Figure 5). If $k_c = 0.5$, we obtain a more stable technological process, the highest value of P_{avg} is characterized by the same conditions as in the previous case (Figure 6). When the value of the stability factor is equal to one, the technological process is stable (Figure 7).

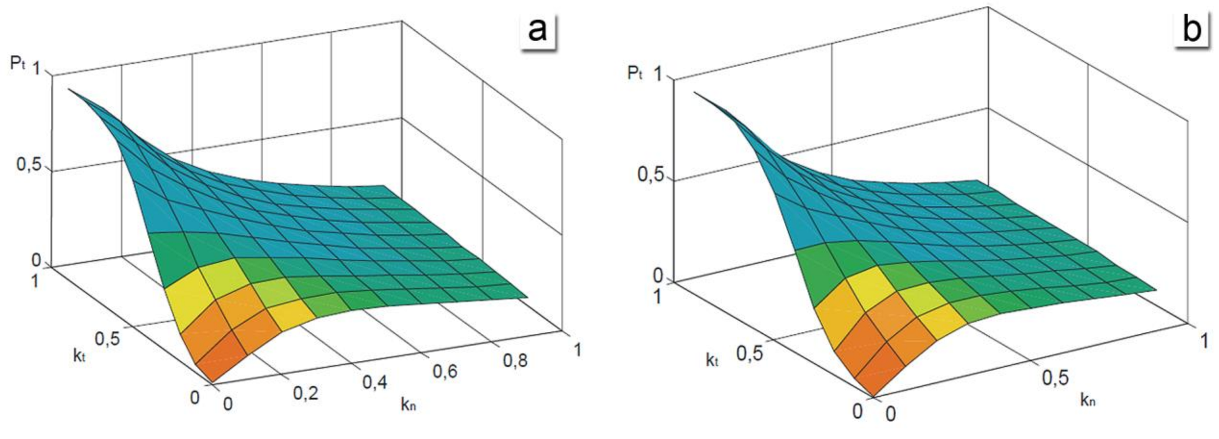

Fig. 5 Dependence of $P(k_t, k_n)$ at $k_c = 0.1$
a) for the size D_{n_1};
b) for the size D_2.

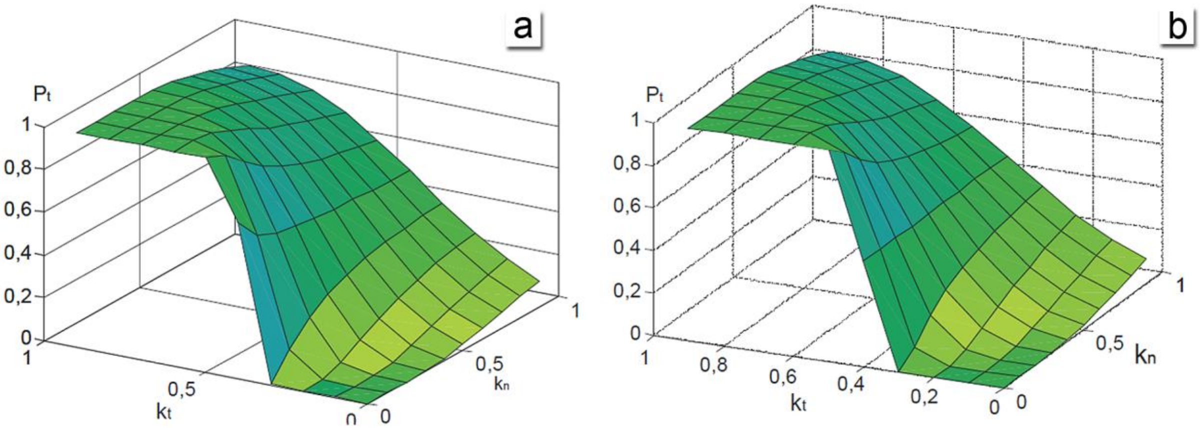

Fig. 6 Dependence of $P(k_t, k_n)$ at $k_c = 0.5$.
a) for the size D_{n_1};
b) for the size D_2.

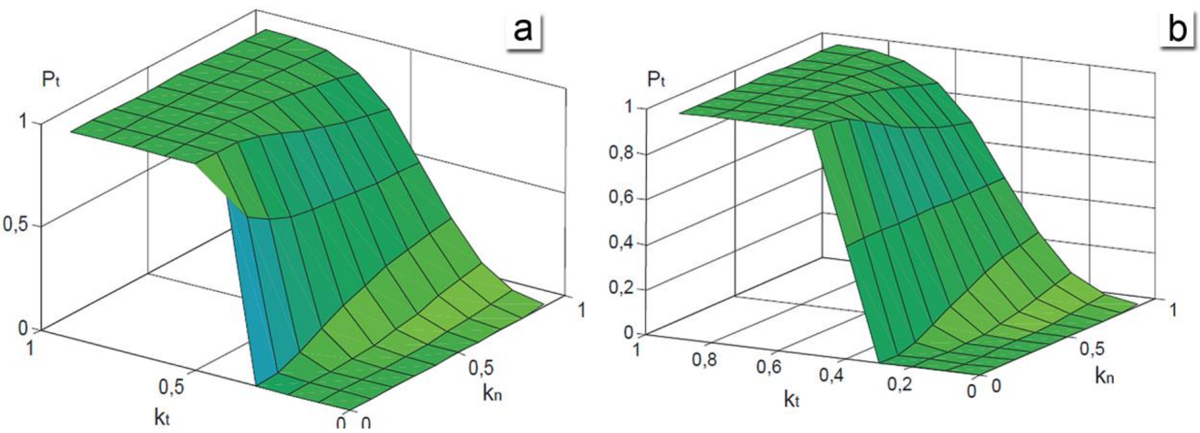

Fig. 7 Dependence of $P(k_t, k_n)$ for $k_c = 1$
a) for the size D_{n_1};
b) for the size D_2.

It can be seen from the figures that the higher the accuracy, mood, and stability coefficients approach the characteristics of an ideal technological process, the higher the generalized quality criterion. In Figure 8, in the form of dots, there are surfaces showing how the coefficients k_t, k_n, k_c should be for P to be greater than 0.9.

To assess the quality level of the batch of key elements in the process of conducting statistical acceptance control, a series of sequential analyzes is used.

The graph of the sequential analysis is constructed using the equations of the Wald's binomial probability ratio, but since in this case, we have to deal with a relatively small amount of rejected products, we can replace the binomial distribution with the Poisson distribution. The initial parameters

of the calculation are the risks of the manufacturer and the customer (α, β), an acceptable and guaranteed quality level (p_1, p_2). Equations, which include these parameters, look like:

$$R_1 = \frac{\lg[(1-\alpha)/\beta]}{\lg\{(p_2/p_1)\cdot[(1-p_1)/(1-p_2)]\}} \tag{11}$$

$$R_2 = \frac{\lg[(1-\beta)/\alpha]}{\lg\{(p_2/p_1)\cdot[(1-p_1)/(1-p_2)]\}} \tag{12}$$

$$S = \frac{\lg[(1-p_1)/(1-p_2)]}{\lg\{(p_2/p_1)\cdot[(1-p_1)/(1-p_2)]\}} \tag{13}$$

To simplify the task, we accept:

$$g_1 = \lg(p_2/p_1);\ g_2 = \lg[(1-p_1)/(1-p_2)];\ a = \lg[(1-\beta)/\alpha];\ b = \lg[(1-\alpha)/\beta].$$

After substituting these quantities into Eqs. (11) - (13), we obtain:

$$h_1 = \frac{b}{g_1+g_2};\ h_2 = \frac{a}{g_1+g_2};\ S = \frac{g_2}{g_1+g_2}.$$

The quantities h_1, h_2, S are the characteristic constants that make it possible to plot the sequence analysis graph. It reflects the characteristic constants and acceptance and rejection lines (Figure 9), the abscissa is the number of tests (from 0 to n), and the accumulated number of discrepancies detected in the verification step (from 0 to f) is plotted along the ordinate axis.

Parallel lines indicate the limits that are used to determine whether the sample matches or does not match the specified quality, with the required confidence level.

The condition of nonconformity is the case when the number of accumulated discrepancies lies on the line or above the rejection line (f_2):

$$f_2 = S \cdot n + h_2$$

If inconsistencies are between the lines, a decision is made to continue the inspection. The condition of conformity is the case when the accumulated number of discrepancies lies on the line or below the acceptance line (f_1):

$$f_1 = S \cdot n - h_1 .$$

In addition, the conclusion on rejection can be made whenever the accumulated number of discrepancies reaches or exceeds the line of rejection; However, the conclusion of compliance can be made only after some minimum number of checks. This minimum quantity is defined as the intersection point of the acceptance line with the abscissa axis.

Figure 10 shows a graph of sequential analysis for the virtual lot in the volume of 1200 pieces.

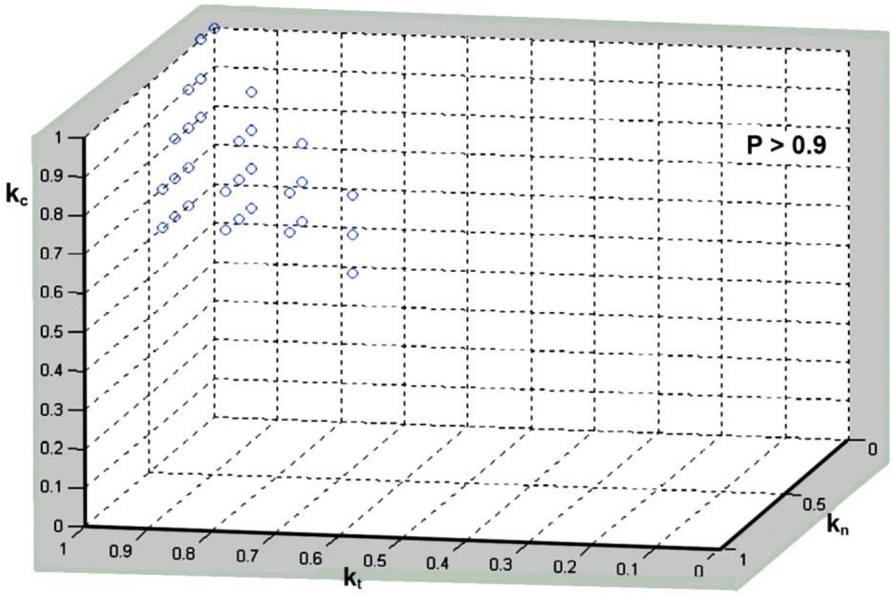

Fig. 8 Surfaces of quality criteria for high-tech process

4. Development of a simulation model of the selective assembly.

As it was shown earlier, in the mass production, the quality of the technical characteristics of the EC is significantly dependent on technological errors in the production of the size parameters of the core. And the influence of each of the individual dimensional parameters on the characteristics is not the same, that is, it has an individual character [15].

For each type of EC there is a special group of key dimensional parameters whose influence of errors on the stability of the characteristics is the most significant. Analysis of the key dimensional parameters of the EC installed in the car shows that the main linear dimension parameters, from the point of view of the effect on the stability of the characteristics, are the parameters forming the working air gap: the internal diameter of the stator and the outer diameter of the rotor [16].

The value of the working air gap determines the individuality of the characteristics of the EC and the technical device in which it is part. In other words, the technological errors of the key dimensions of the active zone of the EC affect the quality and reliability of not only the node or system in which it is part but also affect the corresponding indicators of other systems and the car as a whole [17]. It is possible to achieve an increase in the stabilization of the characteristics of EC in mass production in two ways: by tightening technical conditions and, as a result, by lowering the maximum allowable geometric tolerance for key sizes or by individually selecting assembly units for key dimensional parameters.

In many cases, the application of the first method is unacceptable from an economic point of view, since the tightening of the geometric tolerance field is always associated with the need to meet the requirements for improving the technological accuracy of production, and this is the increase in the cost of new equipment [18].

On the other hand, to date, the failure of electrical equipment arising during the operation of the car is largely eliminated by replacing the appropriate technical device (starter, generator, electromechanical power steering, etc.). This is due to the inability to provide the required level of repair quality of complex electromechanical devices in the conditions of service network enterprises, as well as the absence of expensive repair and testing equipment at such enterprises. Hence, the possibility of using the second method of stabilizing the technical characteristics of the EC - the appropriate selection of the key group of dimensional parameters in the assembly of products, i.e. organization of selective assembly [19–22].

The costs of organizing a selective assembly are limited to ensuring active control of key parameters with identification of assembly units, the introduction of a portal for the accumulation of stators, rotors, and the use of an appropriate information system.

To organize a selective assembly according to the main parameters of the electromechanical converter, it is necessary to predict the results of the selection of individual parameters. To implement this task, we developed a simulation model for the corresponding process, the structure of which is shown in Figure 9, and the algorithm of work in Figure 10

Input data for the model are arrays of stator and rotor dimensions, as well as the air gap accuracy factor. The model consists of generator modules, portal loading, optimization, filtering, and analysis.

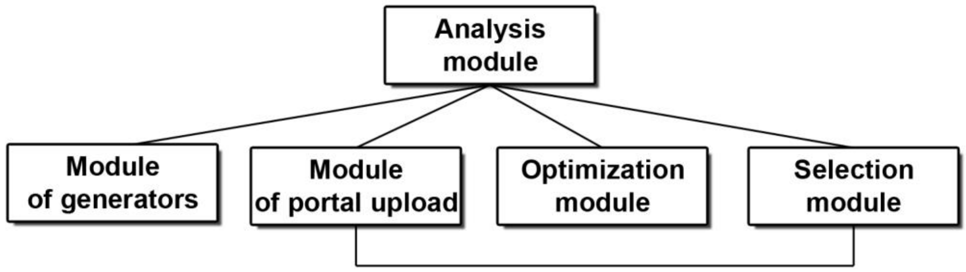

Fig. 9 Structural diagram of the simulation model of selective assembly of EC

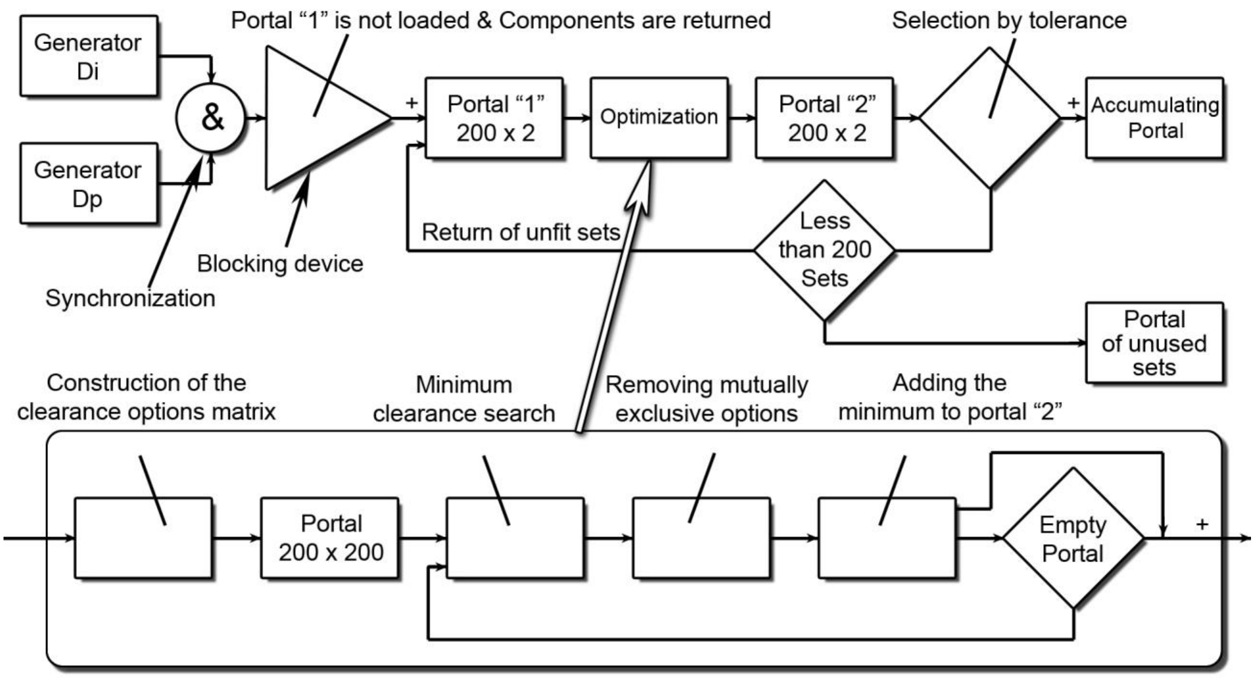

Fig. 10 Algorithm of the model of selective assembly

The generator module is responsible for generating the dimensional parameters of the outer diameter of the rotor and the inner diameter of the stator package. The module outputs the result with a predetermined normal distribution law, where the standard deviation is equal to one-third the span of the tolerance to the rotor or stator [23–25].

In this case, the generators take into account the probability of the part getting out for the tolerance of 0.9973, thereby excluding the possibility of getting in the model of the defective parts (Fig. 11 here the probability value is a single criterion of manufacturing quality of the size parameter.

Next, the system collects the generated virtual rotors and stators into a portal of 200 pairs. The portal upload module is responsible for forming a portal of pairs of stator-rotor components for their

subsequent pairwise optimization. The portal loads first from the pairs returned from the previous iteration. The remainder of the portal is occupied by new pairs generated in the generator module. Pairs from the previous iteration take precedence over newly arriving pairs [26,27].

After the portal is fully loaded with 200 × 2 elements, they are transferred to the optimization module. The optimization module provides the choice of the best combinations of stator-rotor pairs. The filter module provides a selection of parts that meet the requirements. At this stage, the model creates a matrix of 200 × 200 elements with all possible variants of a pairwise stator-rotor connection. The zero value of the deviation of the working air gap corresponds to the optimal ratio of the stator and rotor parameters, and negative and positive values reflect the less successful pairs of sets.

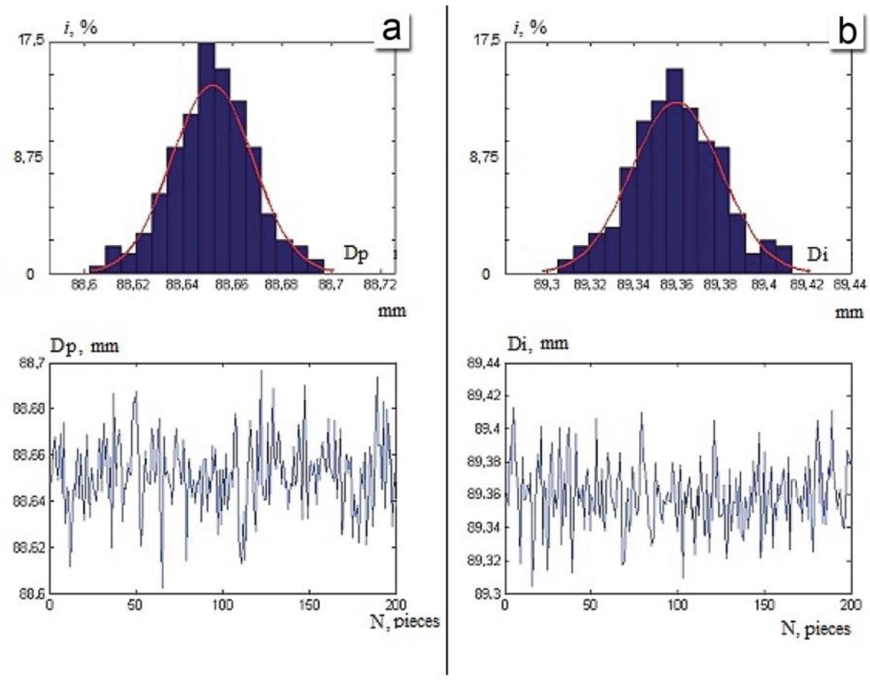

Fig. 11 Work of generators of virtual rotors and stators:
a) the process of generating a rotor size parameter in millimeters by the number of pieces sold;
b) the process of generating a stator dimensional parameter in millimeters by the number of implementations of pieces.

After finding the optimal pair with the minimum deviation from the nominal, all mutually exclusive variants of the pairs are removed from the matrix. The cycle repeats until all the optimal combinations are found. Pairs that do not meet the requirements are returned for re-optimization to the portal load module [28–31]. The system provides an opportunity to exit from a stable state when the number of optimized pairs occupies the entire portal. In this case, it makes an emergency reset and full unloading

of the portal, with the subsequent loading of new pairs. At this stage, the model creates a matrix of 200 × 200 elements with all possible variants of a pairwise rotor-stator coupling.

For greater clarity, we demonstrate the matrix of variants in the form of a three-dimensional surface, shown in Figure 12

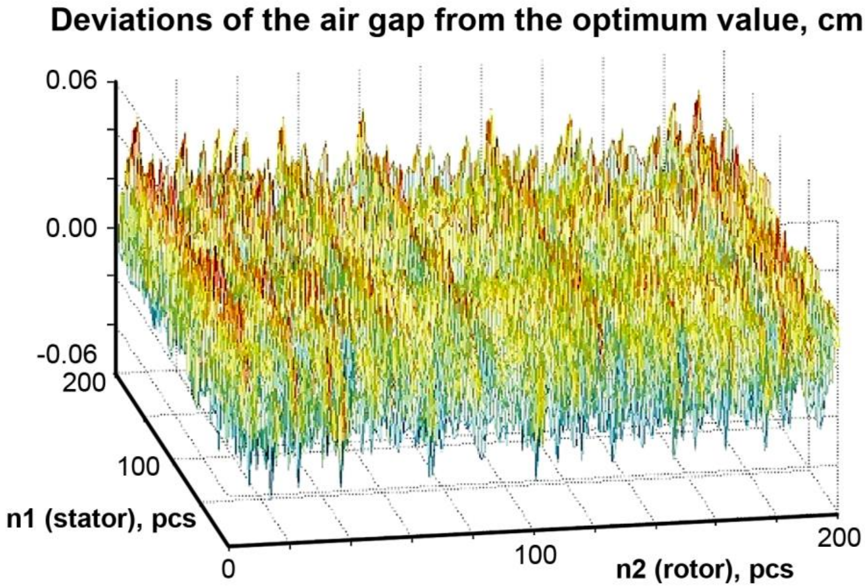

Fig. 12 Visualization of variants matrix

Figure 13 shows histograms and graphs, which clearly show the difference in air gap stability when manufactured by standard methods and using a selective assembly. As can be seen from Figure 14, at the output of the system, the deviation of the air gap is not uniformly distributed, but increases in absolute value, which is explained by the optimization principle itself. This feature can be used if you want to divide the lot into different classes of precision manufacturing. But in this case, the accuracy of the gap in the resulting sets satisfies our conditions. Also, this feature provides a 92% EC output with a 2-fold lower air gap than originally set at the filter output.

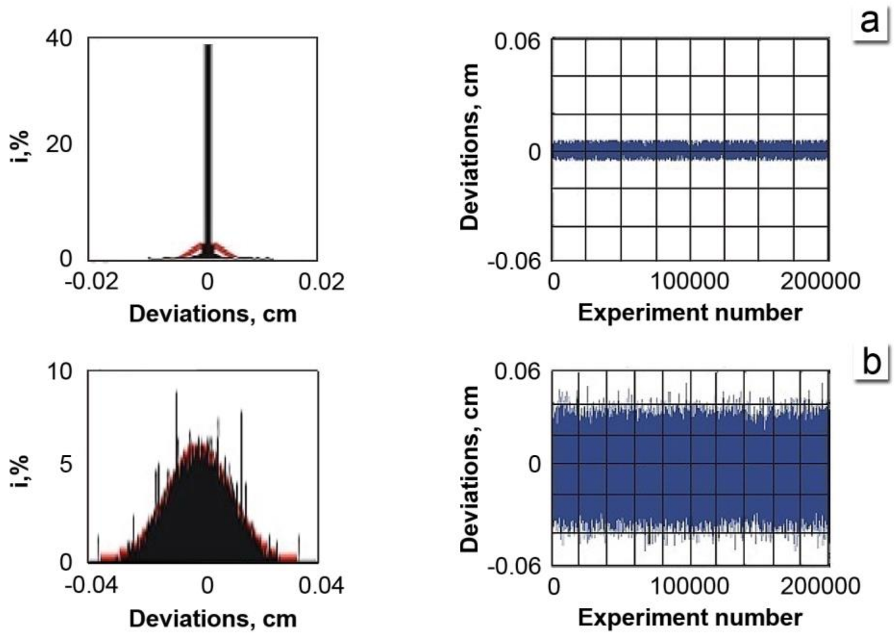

Fig. 13 Histograms and graphs of air gap deviations for selective and standard assembly.

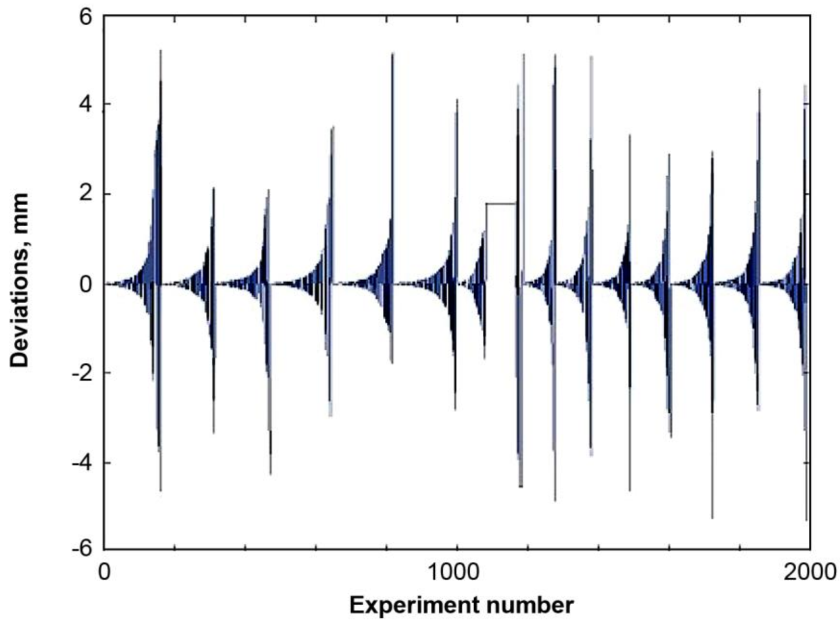

Fig. 14 Diagram of deviations of the air gap with selective assembly.

Thus, through the application of selective assembling by key parameters, the stability of the working air gap size of the EC increases substantially and, as a consequence, the stability of the technical characteristics is increased. The increase in the stability of the EC characteristics ensures an improvement in the quality and reliability of the functioning of the electrical equipment system, and hence the car as a whole. From an economic point of view, the use of a selective assembly is more

justified, since the costs of its organization are incommensurably smaller than the corresponding costs when introducing measures to improve the accuracy of the technological process of production of EC.

5. Conclusions

As a result of the work, a computer model was constructed that combined the elements of the design, production and quality management processes. The model consists of four large structures in which the interrelation between the input size parameter and the output electromagnetic is made, a general quality index is determined and theoretical analysis of the manufacturing process is performed, in accordance with the above, construction and optimization of acceptance inspection plans are carried out.

Further on the basis of the quality index, the organization of selective assembly of technical devices is carried out, and the search for the best combination of key dimensional parameters that ensures the stability of the technical characteristics of the products is carried out. The complexity of the organization of the model of quality management and selective assembly directly depends on the number of key dimensional parameters of the device allocated at the stage of calculation of the coefficients of influence.

Therefore, for the maximum efficiency of its functioning, such a system should be developed that allows monitoring product quality on the basis of process indicators by key parameters, and the selective model is implemented for special groups of key parameters, whose influence on technical characteristics is the most significant.

Funding

The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2020-934 dated 17.11.2020).

Ethical Approval. Not applicable**.**

Consent to Participate:

The authors have consent to participate.

Consent to Publish:

The authors have consent to publish.

Authors Contributions:

Study conception and design: Vladimir Kozlovsky

Acquisition of data: Yury Klochkov

Analysis and interpretation of data: Vladimir Kozlovsky

Drafting of manuscript: Yury Klochkov

Competing Interests. There is no any conflict of interest to declare.

Availability of data and materials: The data that support the findings of this study are available from the corresponding author

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Table 1: Input parameters of the simulation model of the main group devices

№	Parameter	Size , m	Lower and upper value of limits, m
1	2	3	4
Three-phase synchronous alternator with electromagnetic excitation			
1.	Dp outer diameter of the rotor	0.088	-0.0001; 0
2.	Di internal diameter of the stator	0.089	0; 0.00012
3.	li boring length of stator	0.025	0; 0.00084
4.	Dvt bushing diameter	0.043	-0.00025; 0
5.	lst joint length	0.00005	-0.00001; 0.00001
6.	Dm internal diameter of the pole system	0.068	0; 0.00005
7.	lvt bushing length	0.03	0; -0.0021
Three-phase synchronous alternator with excitation from permanent magnets			
1.	Di internal diameter of the stator	0.089	0; 0.00012
2.	Li internal diameter of the stator	0.025	0; 0.00084
3.	Dp outer diameter of the rotor	0.088	-0.0001; 0
4.	Dmag outer diameter of the magnet	0.078	0; 0.00005
5.	dmag inside diameter of a magnet	0.042	-0.00025; 0
6.	lst joint length	5×10^{-5}	-0.00001; 0.00001
7.	lmag length of magnet	0.028	0; -0.0021
Electrostarters based on direct current EC with excitation from permanent magnets			
1.	Dp1 internal diameter of poles	0.068	0.0001; 0
2.	Dp2 anchor diameter	0.065	0; -0.0001
3.	L0 armature length	0.049	0; -0.0005
4.	Lc1 body length	0.015	0.00025; 0
5.	bcor body width	0.006	0.0002; 0
Electrostarters on the basis of direct current EC with electromagnetic excitation			
1.	Dp1 internal diameter of the pole system	0.0786	0.0001; 0
2.	Dp2 outer diameter of pole system	0.078	0; -0.00012
3.	L0 rotor packet length	0.093	0; -0.0015
4.	Lc1 body length	0.018	0.00025; 0
5.	bcor body width	0.006	0.0002; 0
Motor - reducer of window regulator			
1.	Dp1 internal diameter of poles	0.0556	0.0001; 0
2.	Dp2 outer diameter of pole system	0.055	0; -0.00012
3.	L0 armature length	0.03	0; -0.0015
4.	Lc1 body length	0.045	0.00025; 0
5.	bcor body width	0.006	0.0002; 0
Electromechanical power steering on the basis of a constant-current motor with excitation from permanent magnets			
1.	Dp1 internal diameter of poles	0.0556	0.00025; 0
2.	Dp2 outer diameter of poles	0.055	0; -0.0003
3.	L0 armature length	0.033	0; -0.001
4.	hpaza groove height	0.013	0.0002; 0
5.	bpaza the width of the groove	0.020	0.0002; 0
Electromechanical power steering based on the valve-inductor motor			
1.	D1 internal diameter of poles	0.061	0.001; 0
2.	D2 anchor diameter	0.06	-0.003; 0
3.	bnp slot width of the rotor	0.033	0.0005; -0.0005
4.	bzp rotor pole width	0.017	0.0005; -0.0005
5.	li length of the stack	0.03	0; -0.001
Starter - generator based on an induction-dynamic machine			
1.	Dn1 outer diameter of the stator core	0.244	0; -0.00025
2.	D2 internal diameter of the rotor core	0.245	0.0003; 0
3.	l1 length of stator core	0.04	0.001; 0
4.	l2 core length of the rotor package	0.04	0.001; 0
5.	D1 internal diameter of the stator core	0.17	0; -0.00035

Table 2 :Numerical values of the quality criterion

№	Parameter	Pi	Pcp
1	2	3	4
Three-phase synchronous alternator with electromagnetic excitation			
1.	Dp	0.9973	0.9812
2.	Di	0.9973	
3.	li	0.9973	
4.	Dvt	0.9973	
5.	lst	0.9973	
6.	Dm	0.9973	
7.	lvt	0.9973	
Three-phase synchronous alternator with excitation from permanent magnets			
1.	Di	0.9973	0.9812
2.	li	0.9973	
3.	Dp	0.9973	
4.	Dmag	0.9973	
5.	dmag	0.9973	
6.	lst	0.9973	
7.	lmag	0.9973	
Electro starters based on direct current EC with excitation from permanent magnets			
1.	Dp1	0.9973	0.9865
2.	Dp2	0.9973	
3.	L0	0.9973	
4.	Lc1	0.9973	
5.	bcor	0.9973	
Electro starters on the basis of direct current EC with electromagnetic excitation			
1.	Dp1	0.9973	0.9865
2.	Dp2	0.9973	
3.	L0	0.9973	
4.	Lc1	0.9973	
5.	bcor	0.9973	
Motor - reducer of window regulator			
1.	Dp1	0.9973	0.9865
2.	Dp2	0.9973	
3.	L0	0.9973	
4.	Lc1	0.9973	
5.	bcor	0.9973	
Electromechanical power steering on the basis of a constant-current motor with excitation from permanent magnets			
1.	Dp1	0.9973	0.9865
2.	Dp2	0.9973	
3.	L0	0.9973	
4.	hpaza	0.9973	
5.	bpaza	0.9973	
Electromechanical power steering based on the valve-inductor motor			
1.	D1	0.9973	0.9865
2.	D2	0.9973	
3.	bnp	0.9973	
4.	bzp	0.9973	
5.	li	0.9973	
Starter - generator based on an induction-dynamic machine			
1.	Dn1	0.9973	0.9865
2.	D2	0.9973	
3.	l1	0.9973	
4.	l2	0.9973	
5.	D1	0.9973	

Table 3 Quality Indicators of the production technological process for products of the main group

№	Parameter	kн	kт	kc
1	2	3	4	5
Three-phase synchronous alternator with electromagnetic excitation				
1.	Dp	0.000176	1.129	1.109
2.	Di	0.00078	1.132	0.931
3.	li	0.00103	1.152	1.015
4.	Dvt	0.0008	1.153	1.027
5.	lst	0.00056	1.141	0.767
6.	Dm	0.0012	1.071	0.908
7.	lvt	0.00072	1.124	0.956
Three-phase synchronous alternator with excitation from permanent magnets				
1.	Di	0.000192	1.148	1.1
2.	li	0.00064	1.124	0.99
3.	Dp	0.00921	1.162	1.0
4.	Dmag	0.00062	1.131	1.0
5.	dmag	0.00036	1.152	0.89
6.	lst	0.0009	1.1	0.901
7.	lmag	0.00098	1.11	0.985
Electrostarters based on direct current EC with excitation from permanent magnets				
1.	Dp1	0.00492	1.173	0.997
2.	Dp2	0.00505	1.075	1.001
3.	L0	0.00493	1.13	0.936
4.	Lc1	0.00496	1.202	1.002
5.	bcor	0.00504	1.107	0.995
Electrostarters on the basis of direct current EC with electromagnetic excitation				
1.	Dp1	0.00499	1.05	0.992
2.	Dp2	0.00554	1.075	1.09
3.	L0	0.0045	1.137	0.967
4.	Lc1	0.00499	1.102	1.075
5.	bcor	0.0021	1.12	0.991
Gear motor electric window				
1.	Dp1	0.00395	1.05	0.89
2.	Dp2	0.00482	1.068	1.02
3.	L0	0.0035	1.082	0.98
4.	Lc1	0.00372	1.09	1.02
5.	bcor	0.0018	1.056	0.9
Electromechanical power steering on the basis of a constant-current motor with excitation from permanent magnets				
1	2	3	4	5
1.	Dp1	0.00492	1.173	0.997
2.	Dp2	0.00505	1.075	1.001
3.	L0	0.00493	1.13	0.936
4.	hpaza	0.00496	1.202	1.002
5.	bpaza	0.00504	1.107	0.995
Electromechanical power steering on the basis of the valve-inductor motor				
1.	D1	0.004926	1.102	0.992
2.	D2	0.00321	1.021	1.022
3.	bnp	0.0012	1.15	0.952
4.	bzp	0.00214	1.112	0.842
5.	li	0.00231	1.04	0.989
Starter - generator based on an induction-dynamic machine				
1.	Dn1	0.00221	1.071	1.002
2.	D2	0.0012	1.0121	0.998
3.	l1	0.00142	1.002	1.0
4.	l2	0.0018	0.998	0.999
5.	D1	0.00152	1.045	0.842

Figures

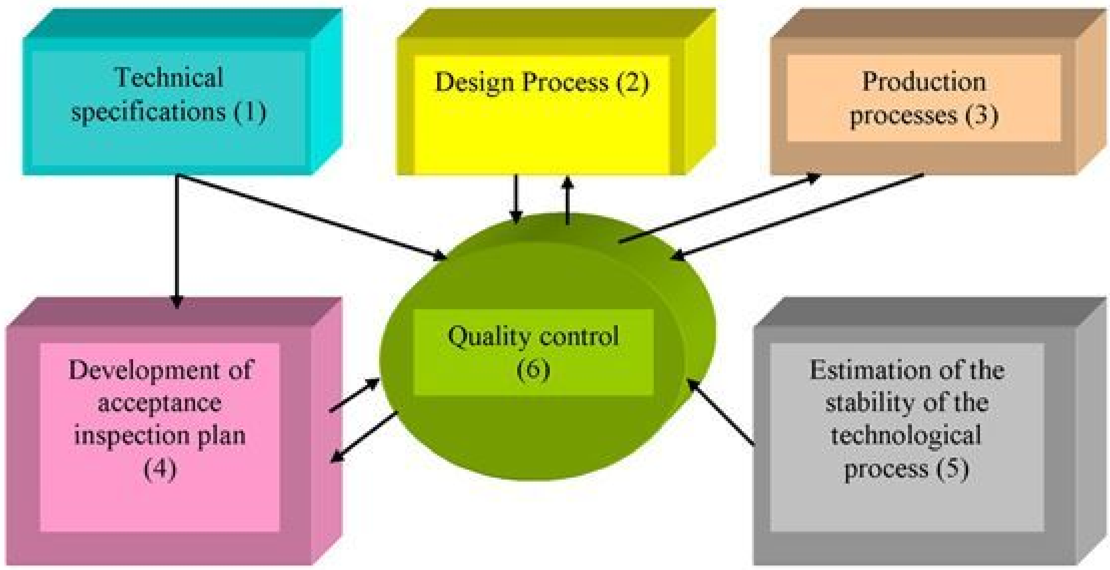

Figure 1

The process of creating a product

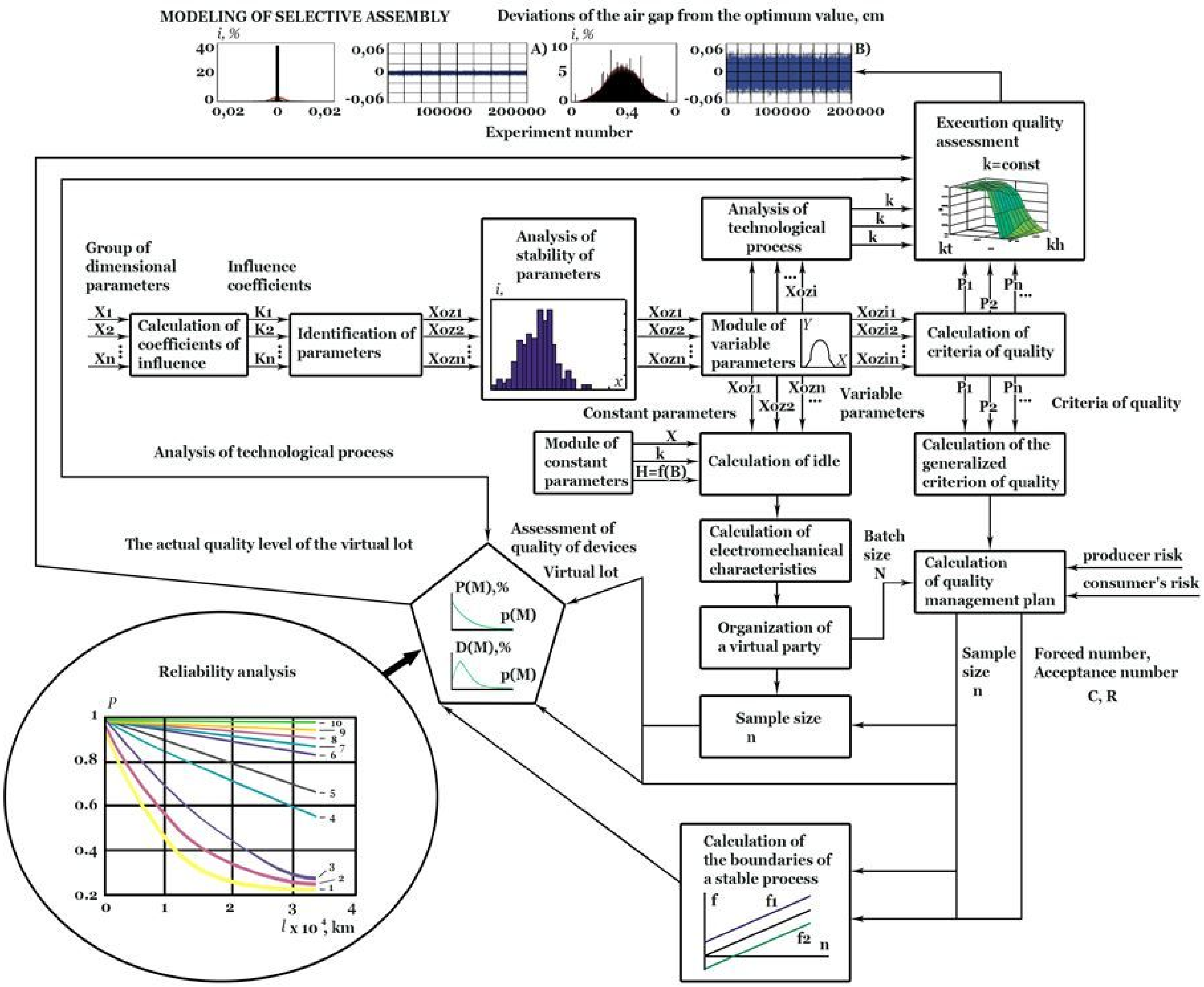

Figure 2

The structure of the integrated model

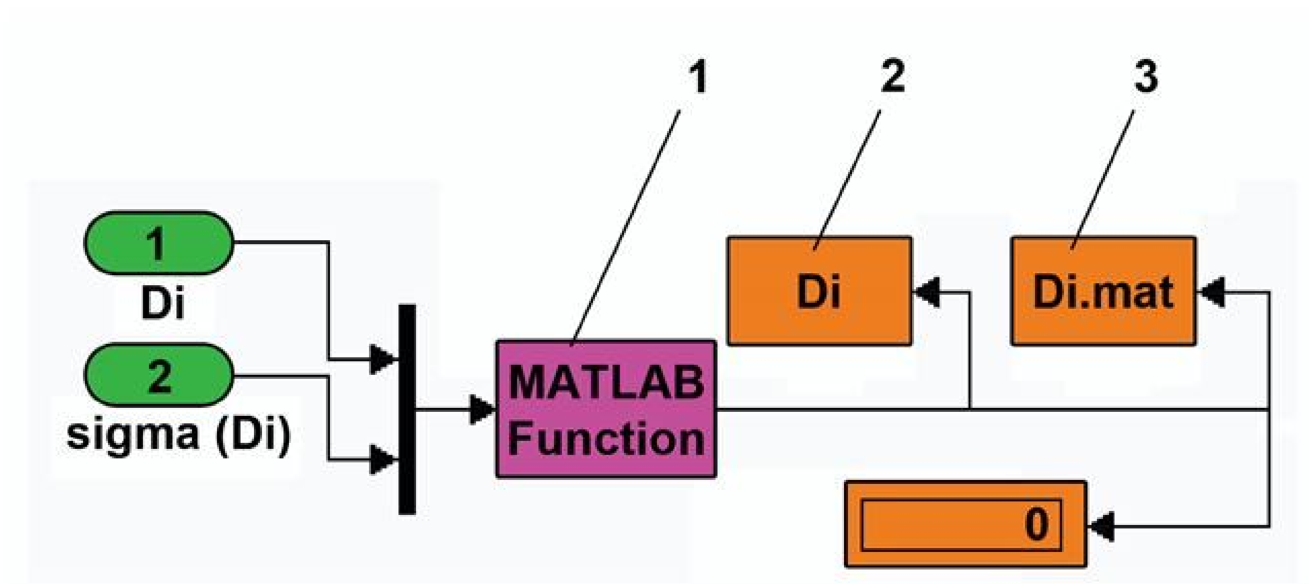

Figure 3

The organization of the random number generator in the model describing the technological process of production of the basic elements of electrical equipment.

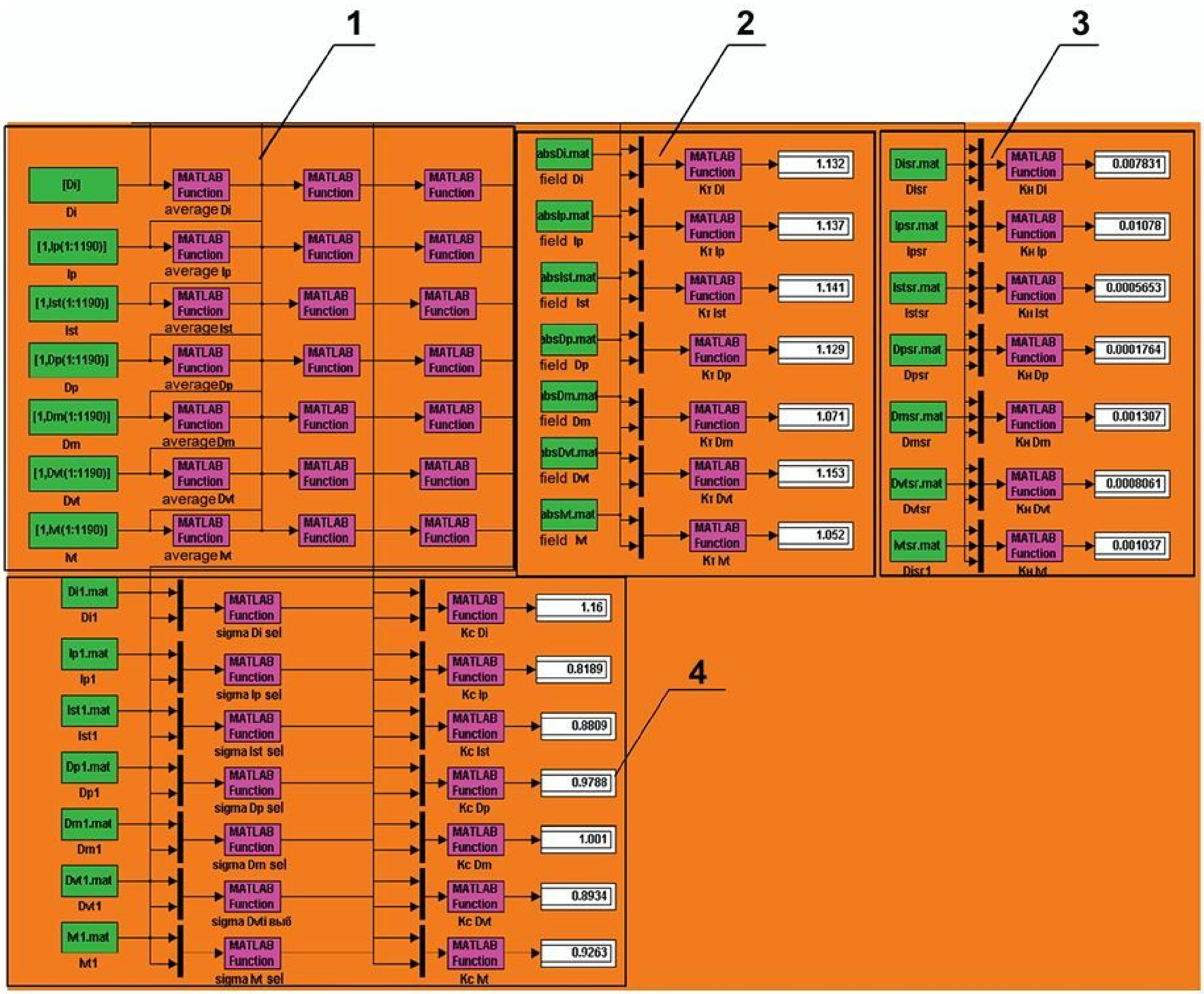

Figure 4

Steady technological process parameter estimation module

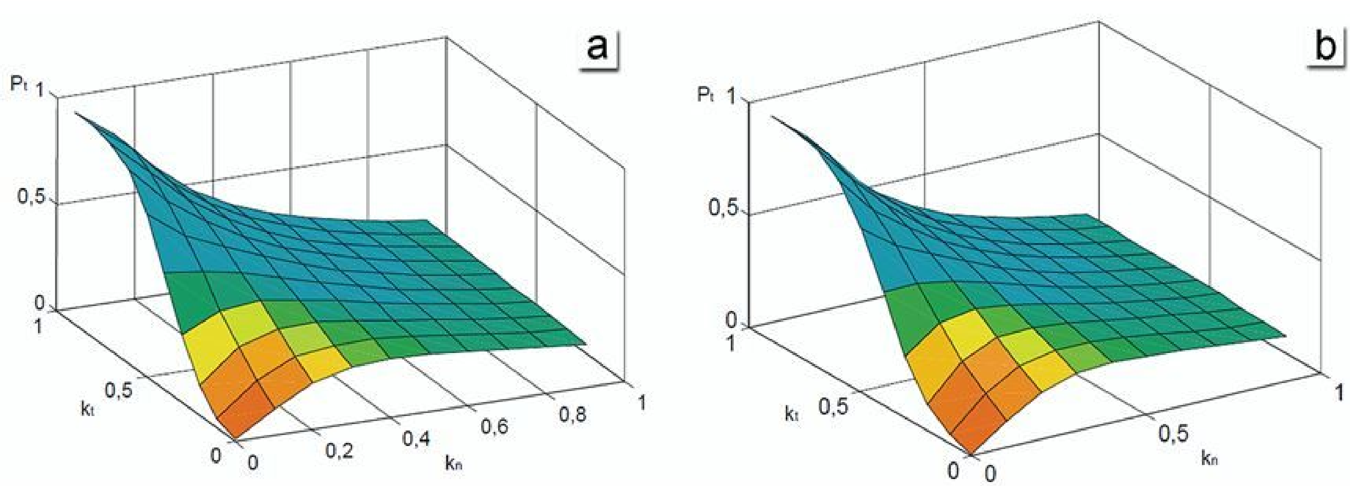

Figure 5

please see the manuscript file for the full caption

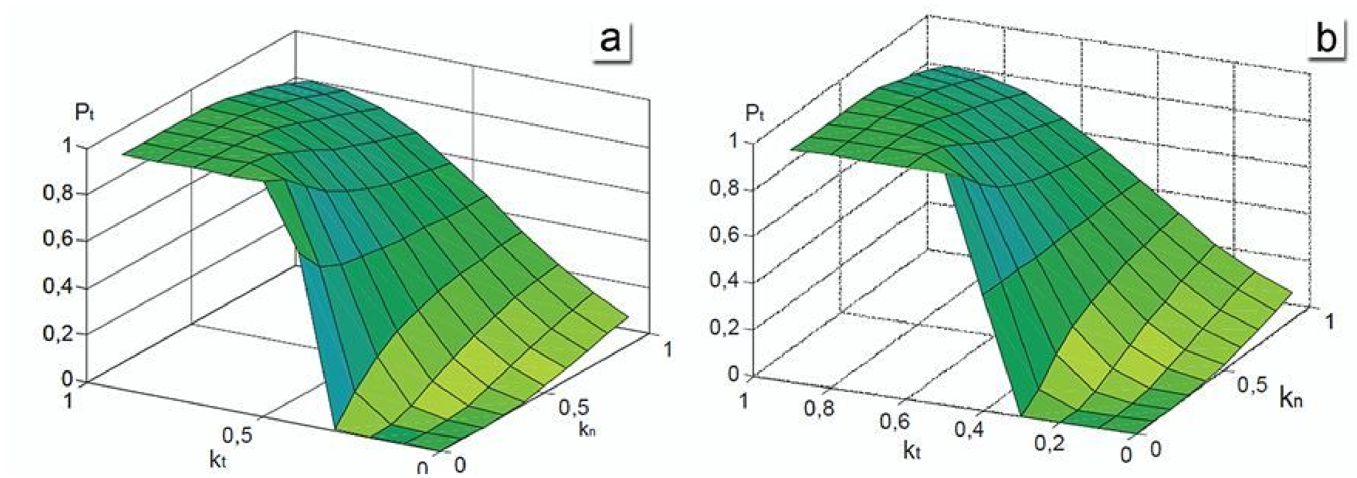

Figure 6

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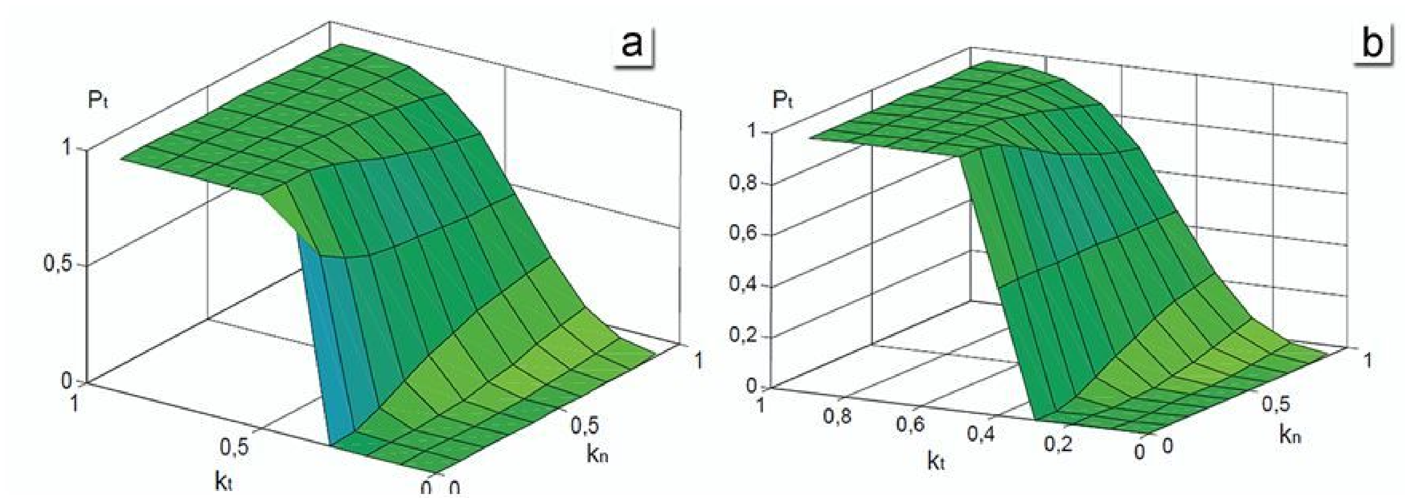

Figure 7

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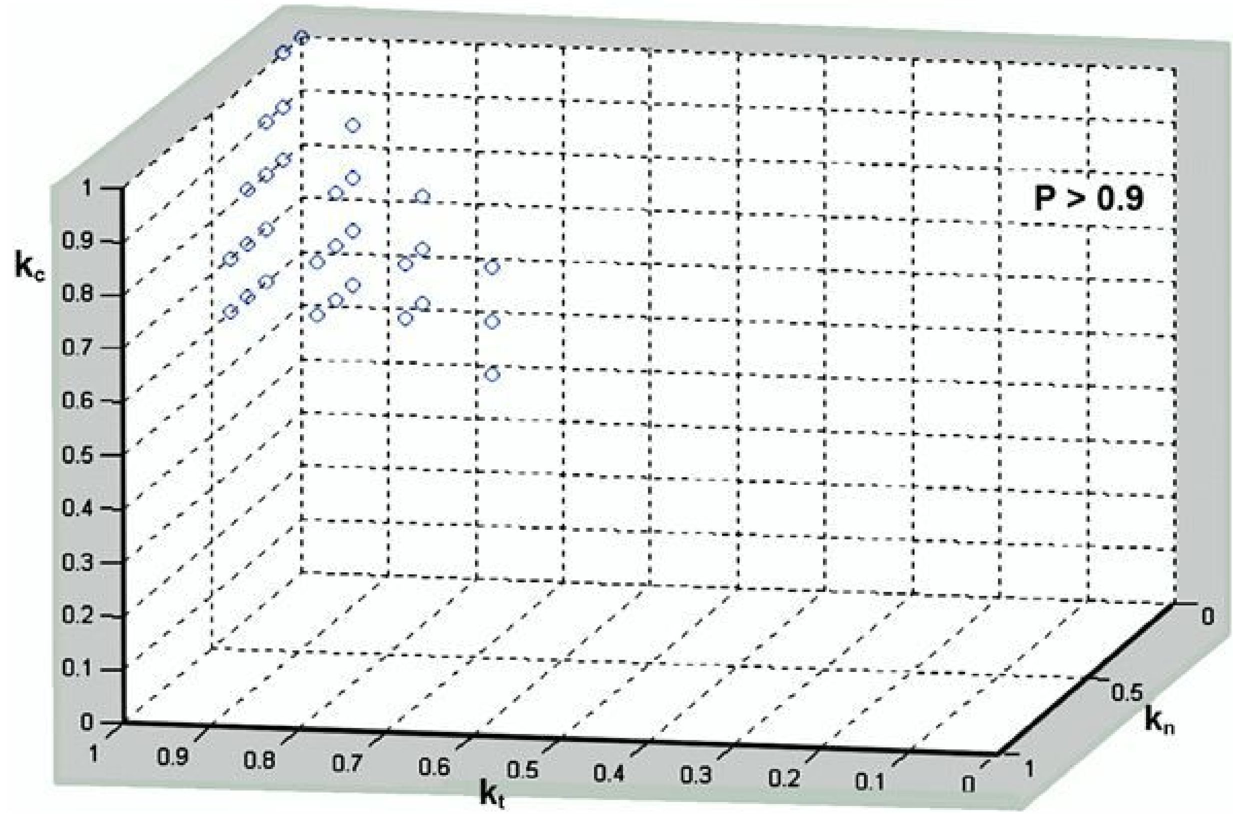

Figure 8

Surfaces of quality criteria for high-tech process

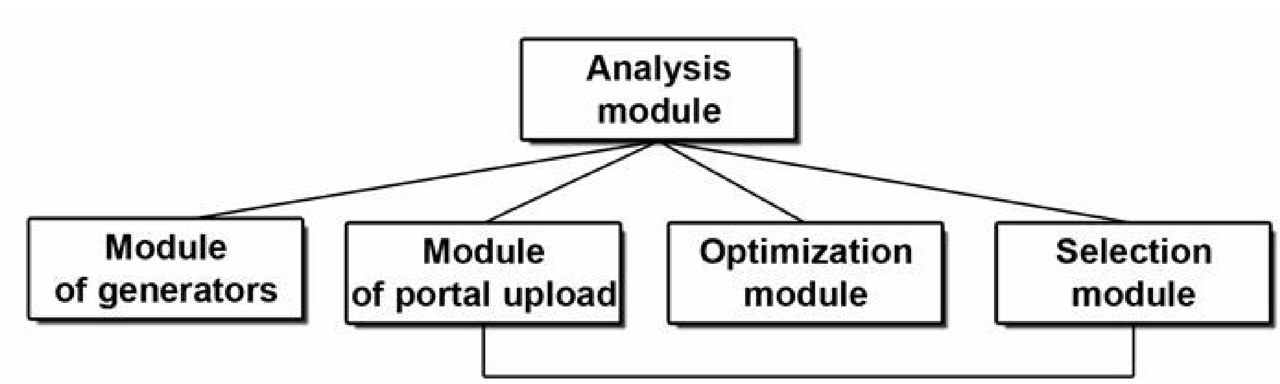

Figure 9

Structural diagram of the simulation model of selective assembly of EC

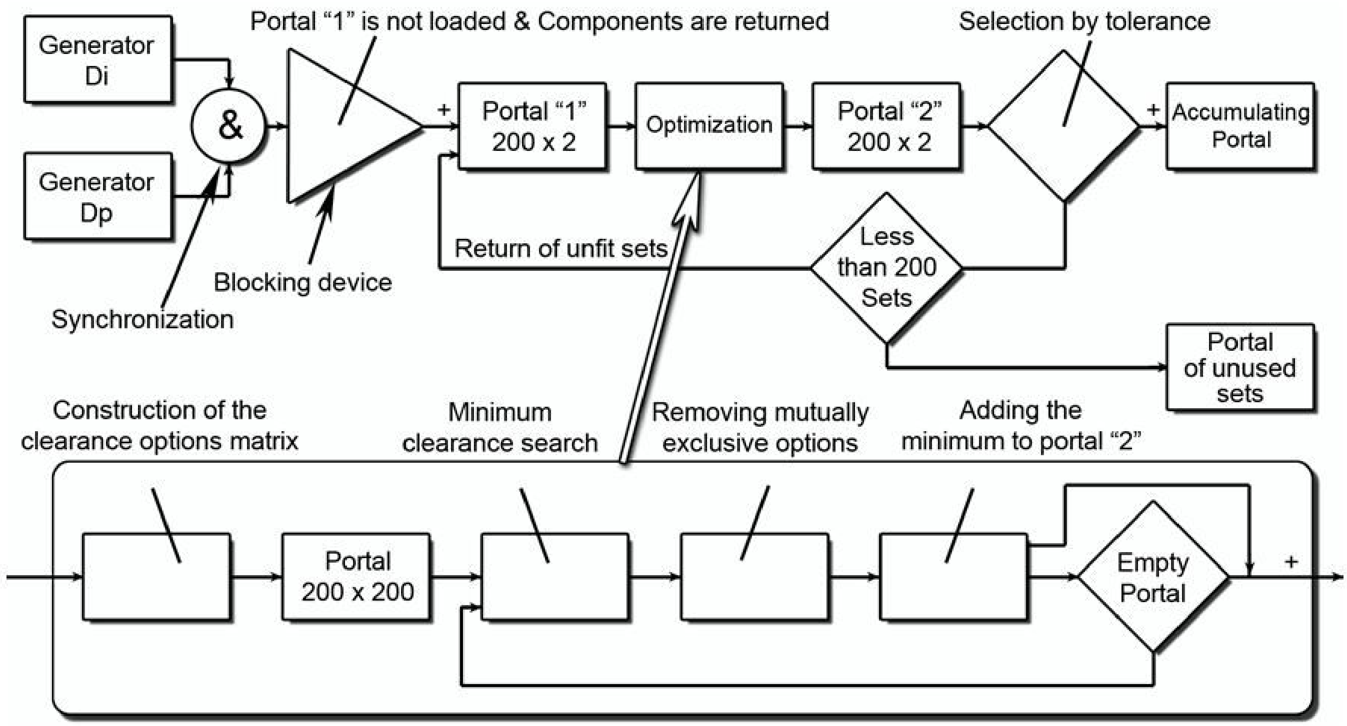

Figure 10

Algorithm of the model of selective assembly

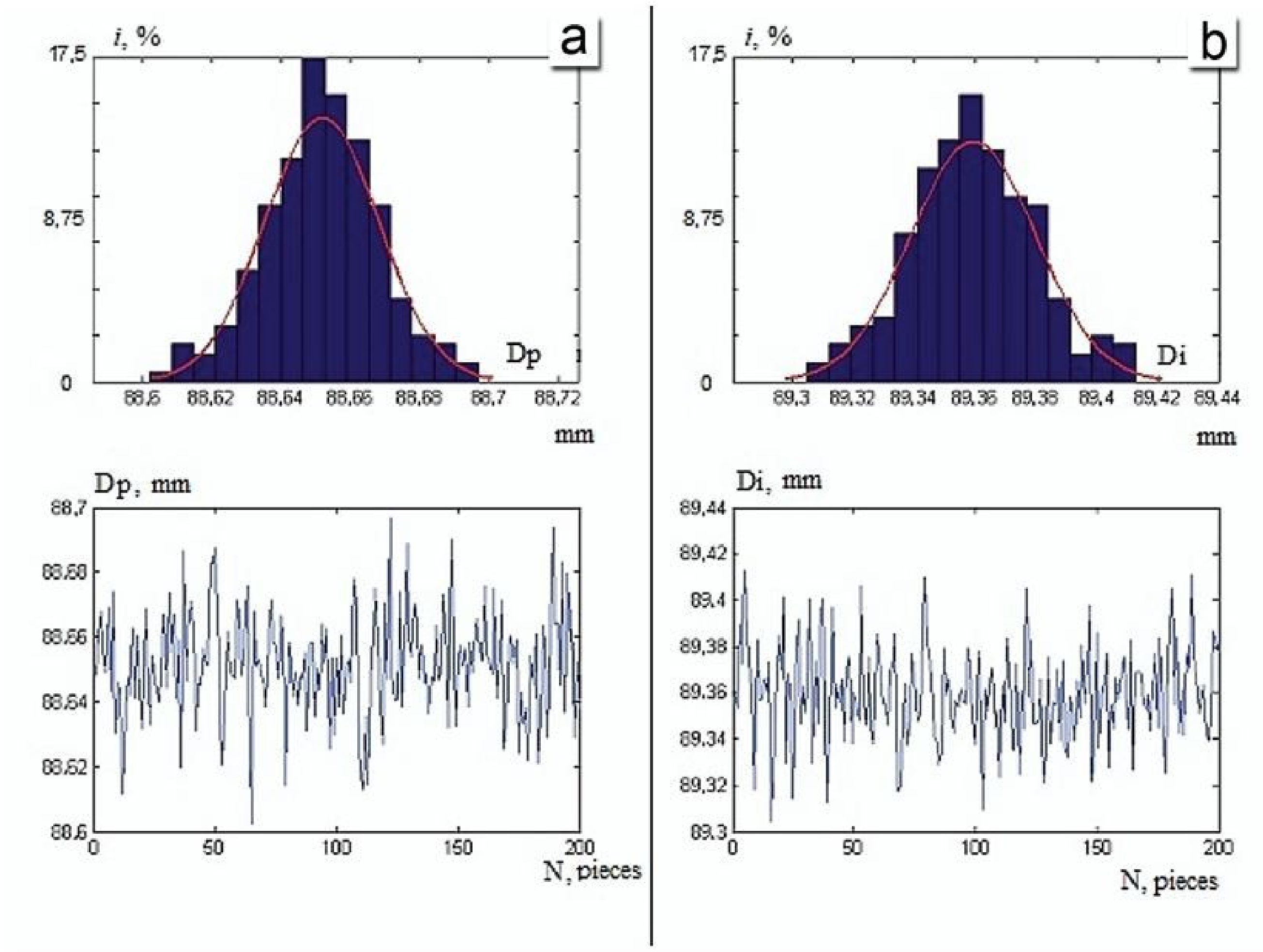

Figure 11

Work of generators of virtual rotors and stators: a) the process of generating a rotor size parameter in millimeters by the number of pieces sold; b) the process of generating a stator dimensional parameter in millimeters by the number of implementations of pieces.

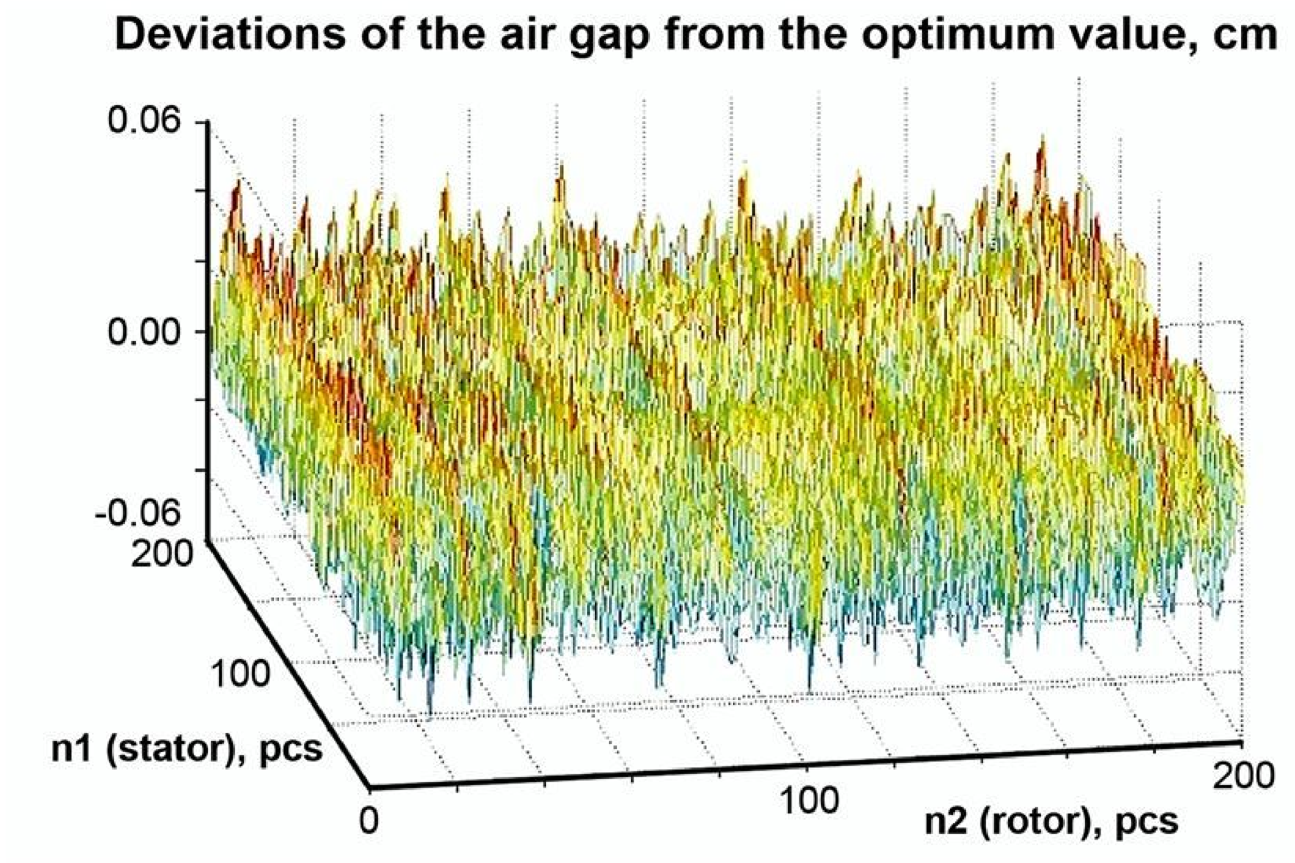

Figure 12

Visualization of variants matrix

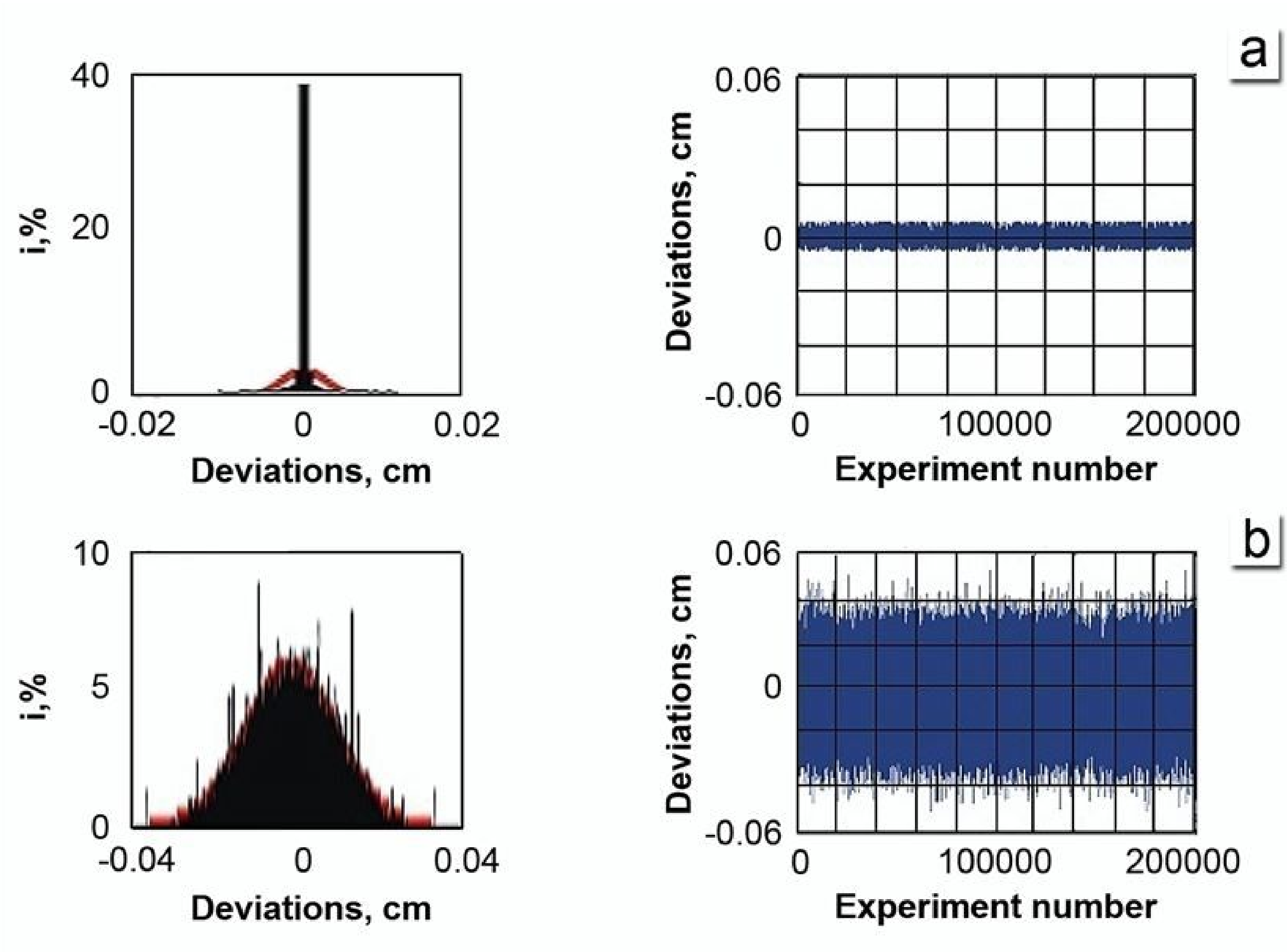

Figure 13

Histograms and graphs of air gap deviations for selective and standard assembly.

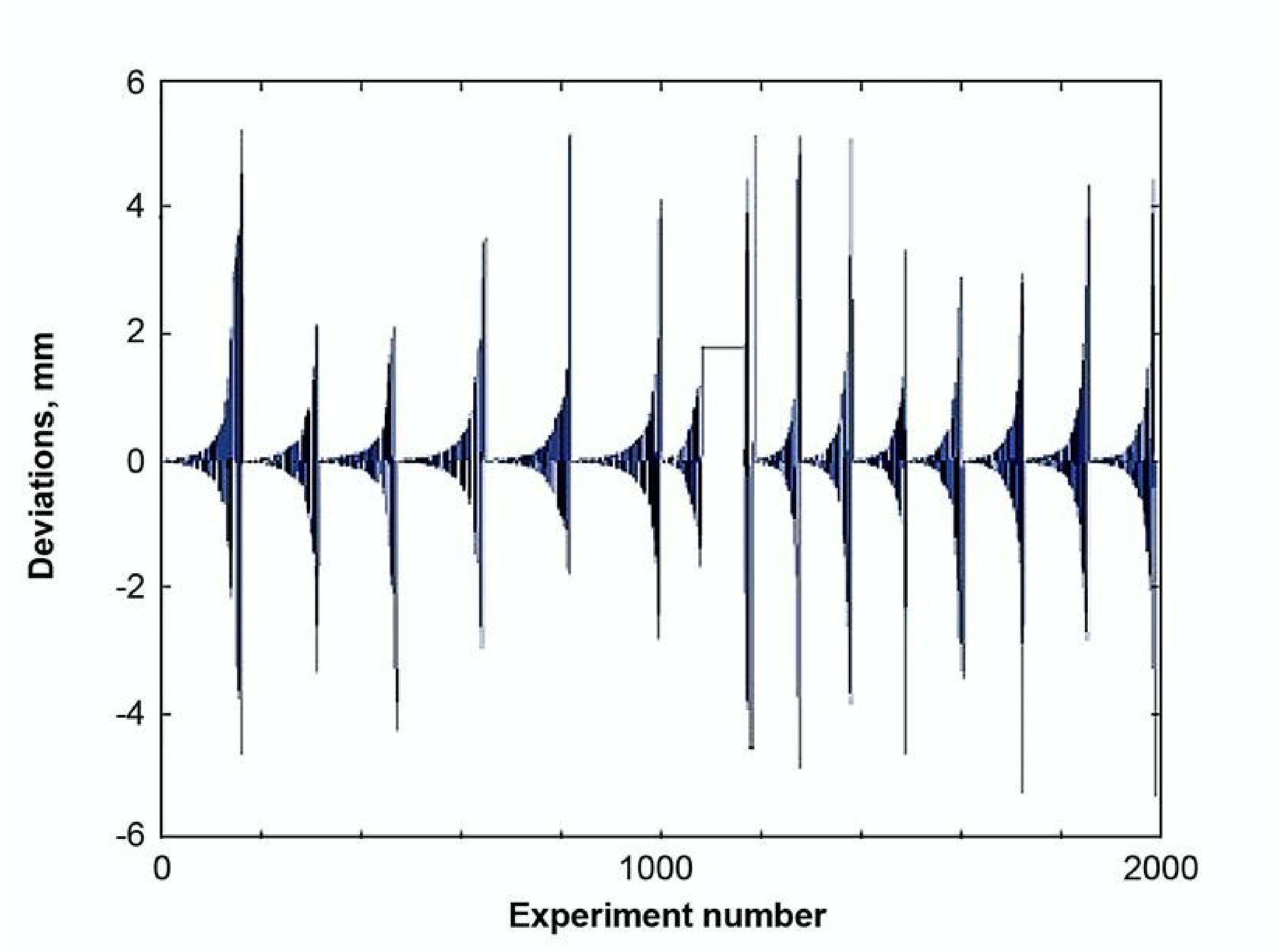

Figure 14

Diagram of deviations of the air gap with selective assembly.