Methodological basics of creating intelligent quality management systems in mechanical engineering

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Abstract. Quality management systems are becoming increasingly widespread in various sectors of the Russian economy, in mechanical engineering in particular. Enterprises and companies claim that they have these systems. In spite of this fact, in practice they often have a limited set of certain procedures that describe a type of quality management actions at certain stages of product creation and service performance. In this article, the author makes an attempt to identify problem points that are connected to the development and implementation of these systems, as well as to plan some ways to improve their effectiveness.

1. Introduction

The requirements of the modern market of engineering products are quite rigid. They make the producers ensure the quality of products. At the same time, the issue of introducing products to the market on time is always significant. It is known that one of the most effective levers for achieving these goals is introduction of an automated product quality control system (QCS) in a company. Therefore, it becomes clear that ensuring the effective functioning of these systems is of high priority.

There are many companies involved in development of quality management systems for consumers. However, achieving effective functioning of QCS in practice is often impossible. This is despite a large documentation package that regulates quality management procedures in companies and available recommendations [1, 2, 5, 6, etc.].

We are going to try to understand the reasons for such a negative situation by answering the following questions.

2. What should be automated quality control systems?

First of all, it should be noted that quality assessment procedures are almost an unformulated task. Therefore, in our opinion it is necessary to provide the following points in an automated system:

a) use of an artificial intelligence device when forming knowledge bases and decision making;
b) ensuring the possibility of an automated system operation involving experts;
c) system openness for tuning to consumers;
d) a system might belong to a hybrid class with various types of artificial intelligence models.

The second important point is that the logic of system operation corresponds to a product life cycle. However, in practice, it often happens that companies neglect an important stage of development of a product technical specification. Therefore, QCS can only determine if a product measures up design documentation that fixes a certain level of product quality. Nevertheless, the question is who determines this level.

Hence, the need to include the stage of development of the technical task for a product into the composition of QCS work stages becomes clear.

As an example, let us consider a QCS model developed according to this provision [7, 8, 18] as a complex system with sub-systems $\{R_0\} = \{R_1^1, R_1^2, ..., R_1^5, R_2^1, R_2^2, ..., R_2^{12}\}$ (figure 1).

Figure 1 represents the QCS subsystem designated as R_0 (subsystem of an upper level). Subsystems of subsequent levels are described below.

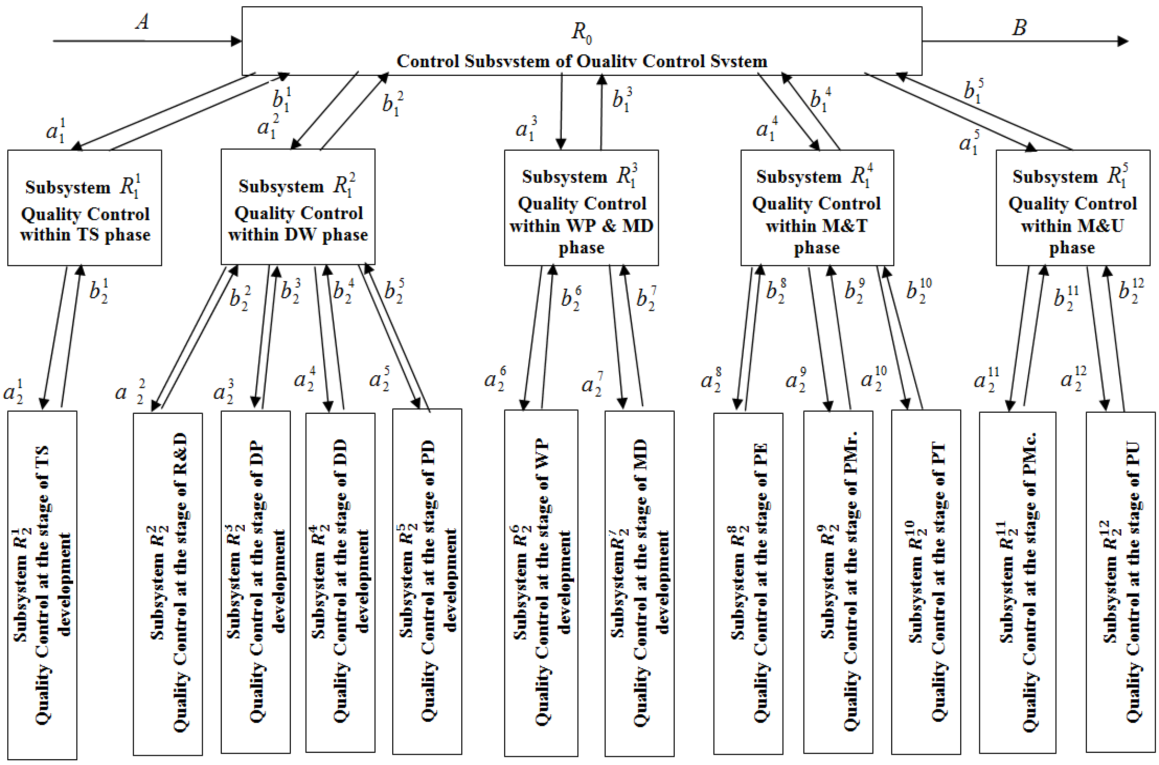

Figure 1. A set-theoretical model of QCS.

Subsystem R_1^1 performs quality control within technical specifications (TS) development phase. It includes subsystem R_2^1 that is quality control at the stage of technical specifications (TS) development.

Subsystem R_1^2 performs quality control within the design work (DW) phase with four life cycle stages. It fulfills the following functions: R_2^2 is quality control at the stage of research (R&D); R_2^3 is quality control at the stage of draft proposal (DP) development; R_2^4 is quality control at the stage of draft design (DD) development; R_2^5 is quality control at the stage of preliminary design (PD) development.

Subsystem R_1^3 performs quality control within the work paper (WP) and maintenance documentation (MD) development phase with two life cycle stages. It fulfills the following functions: R_2^6 is quality control at the stage of WP development; R_2^7 is quality control at the stage of MD development.

Subsystem R_1^4 performs quality control within the product manufacture and testing phase (M&T) with three life cycle stages. R_2^8 is quality control at the stage of process engineering (PE); R_2^9 is quality control at the stage of product manufacture (PM); R_2^{10} is quality control at the stage of product testing (PT).

Subsystem R_1^5 performs quality control within the product maintenance and utilization (M&U) phase, with two life cycle stages. It fulfils the following functions: R_2^{11} is quality control at the stage of product maintenance (Mc); R_2^{12} is quality control at the stage of product utilization (PU).

Control subsystem R_0 has six control functions. The first one is to control subsystem R_1^1, that is to find out and adjust product quality parameters within TS phase: $R_{01}: A \times b_1^1 \rightarrow a_1^1$, where *A* is a control signal that is a set of requirements for product quality parameters at all the stages of PLC under the enterprise management system; b_1^1 is a set of actual product quality parameter values at the stage of TS; a_1^1 is a set of corrective actions on product quality parameters within TS phase.

The second function is to control subsystem R_2^1, that is, to find out and adjust product quality parameters within DW phase: $R_{02}: A \times b_1^2 \rightarrow a_1^2$, where b_1^2 is a set of product quality parameter values within DW phase; a_1^2 is a set of corrective actions on product quality parameters within DW phase.

The third function is to control subsystem R_3^1, i.e. to find out and adjust product quality parameters within WP and MD development phase: $R_{03}: A \times b_1^3 \rightarrow a_1^3$, where b_1^3 is a set of actual product quality parameter values within WP and MD phase; a_1^3 is a set of corrective actions on product quality parameters within WP and MD development phase.

The fourth function is to control subsystem R_4^1, that is, to find out and adjust product quality parameters within M&T phase: $R_{04}: A \times b_1^4 \rightarrow a_1^4$, where b_1^4 is a set of actual product quality parameter values within M&T phase; a_1^4 is a set of corrective actions on product quality parameters within M&T phase.

The fifth function is to control subsystem R_5^1, that is, to find out and adjust product quality parameters within M&U phase: $R_{05}: A \times b_1^5 \rightarrow a_1^5$, where b_1^5 is a set of actual product quality parameter values within M&U phase; a_1^5 is a set of corrective actions on product quality parameters within M&U phase.

At last, the sixth function is to find out the product quality parameters in all the PLC phases: $R_{06}: A \times b_1^1 \times b_1^2 \times b_1^3 \times b_1^4 \times b_1^5 \rightarrow B$, where *B* is an output signal that is a set of end product quality parameters.

This model can serve as a basis for development of design procedures in QCS.

The *third aspect* is related to the criteria for evaluating decisions at QCS work stages.

It seems that evaluation criteria can be quantitative (with boundary values), qualitative (like yes, no) and qualitative with probabilistic nature (the probability of reaching a required level).

Therefore, there is a problem of bringing them to a single evaluation scale [7].

3. Why do we need quality control systems?

It seems a very simple question, but getting a correct answer is often very difficult. Let us try to figure out why by answering the questions listed below.

A. Who should determine the quality of a product?

There is a common answer that it is a producer who determines it. Here you can object, “Does a producer consumes his own products?” Obviously no. If we consider the question of quality even at the level of common sense, it becomes clear that the one who buys products must determine their quality.

Hence, there is a conclusion that an automated quality control system should provide the possibility of analysing product quality required by consumers.

B. How to determine what a consumer wants?

This is the first difficulty for QCS implementation. There are many methods of market research that have varying degree of uncertainty.

In our opinion, the most effective approach might be a preliminary market assessment using marketing technologies included in the automated quality control system, and then production of trial lots. It is clear that such methodology requires investment. Nevertheless, it can secure against big losses when launching programs based on marketing research and advertising.

C. How a consumer mind forms a quality model?

It is very difficult to predict consumer needs without answering this question. In our opinion, the following points determine this procedure.

First.

Unwillingness to perform labour-intensive actions that do not require intellectual expenses. For example, a vacuum cleaner or a washing machine. This case is typical for an ordinary person.

Second.

A desire to increase productivity and improve labour quality or to make it easier. An example is the appearance of more productive machines. This case is typical for a producer of goods and services.

Third.

Obtaining brand new opportunities for leisure or performing new functions by employees, etc., that is, implementation of something that was impossible before.

The first three moments describe “non-imposed” models.

Fourth.

Advertising. In our opinion, the main thing here is not to overdo it, otherwise a consumer might start to refuse an advertised model. It is also important that an advertisement recipient gets accustomed to it. If he does not see a product or service in an advertisement, he begins to doubt its usefulness. On the other hand, long-term advertising of the same leads a recipient to the idea “is it really good?” Relying on this moment only does not allow long-term success, therefore the production of goods is effective for a limited period of time, and does not guarantee their overproduction.

Fifth.

The ability to understand trends in the relevant production field. This approach is useful for high-tech and highly organized industries with highly skilled administrative staff. Unfortunately, it is not so frequent.

To sum up, it is possible to offer the following method of “soft” management of a consumer quality model. Using the approach proposed in the answer to the question B, one should determine a product quality model formed based on the first three moments. Then the prediction of this model trends follows. Based on the forecast one can determine product modification and bring it to the market while unobtrusively showing the advantages of new samples in advertisement.

Summarizing the above, we can conclude that QCS should include marketing technologies and an apparatus that allows experts to build product quality models and predict their trends.

4. How to approach the development of a quality control system?

We can determine several most methodologically significant steps.

4.1. Determination of parameters that describe product quality in QCS

We assume that we have determined the product quality required by a consumer as shown above. In the Japanese system of “lean production” this concept of quality is close to the concept of value.

It is necessary to formally describe this quality to use it in QCS. For this purpose, we need to find out what are the most important product parameters that form its quality. After determining the parameters, it is necessary to find out their allowed intervals.

This is a difficult task and is possible only for the most qualified specialists. Its difficulty is in the fact that the parameters do not always determine quality in an explicit form; the parameters cannot always be a numerical estimate [1, 2, 5, 6, 8].

4.2. Identifying actions that affect product quality

At the second stage, it is necessary to understand what actions in a company affect product quality. This is necessary for understanding time points of a product life cycle in which its quality is monitored.

The main mistake of system developers is to take into account in QCS only those actions that explicitly form product quality (i.e., quality control systems exist on their own, as well as processes in the organization). In industry, these are the processes of production preparation [7, 8, 9, 10, 11]. In our opinion, if we talk about product quality, we should mean its entire life cycle. Here we come to understanding the following facts:

1) product quality cannot be considered in isolation from all processes in a company;
2) quality control is a way of organization functioning;
3) organization activity consists of processes [3, 4, 10].

Therefore, QCS is not an extension to a company automated control system, but its essence.

4.3. Determining organization processes that affect product quality

The basis of any management system including a quality management system is company business processes. Sometimes it is not entirely clear in practice what is the purpose for describing company processes. In other words, "process control" is introduced.

When talking about introducing process control as an end in itself, one can assume only an attempt at optimizing with not completely understandable criteria, ordering functions and eliminating their duplication [11,12,15]. Such approach will not bring great benefits.

When implementing process management, it is necessary to understand what we want to manage. Without such statement of the problem, everything will be reduced to some "improved" administration. Therefore, in practice process management is often based on business activities (accounting, warehouse, production, top management). This shows the problem related to the ability to realize and represent company processes hierarchically linking them also in time.

It should be taken into account that processes are not required to copy a company administrative structure. Moreover, different divisions may be involved in the same process.

Thus, another problem to be solved is the development of a hierarchical process system in QCS. It implies inclusion of lower level processes in higher level ones, which agrees with the content presented in [16, 17, 18].

4.4. Determining process performance criteria in QCS

A system of processes requires building a system of criteria at each hierarchy level aimed at ensuring product quality [8]. These criteria should be based on the concept of product quality supplemented by quality criteria of a particular organization process.

For example, the purchase of raw material. It is clear that the criterion connected with the concept of product quality will be the criterion of raw material quality. However, the process of purchasing raw material implies that it is important to specify exactly which raw material, which parameters, and which supplier it should be (complementary quality criteria). A mandatory additional criterion should be time and the accuracy of function execution of individual operations in the process. It is not an easy task and requires a serious investigation of possible incorrect and inadequate actions.

The principles of forming criteria for evaluating solutions at product life cycle stages can be formulated as follows:

a) the principle of a criteria boundary type;
b) the principle of a criteria relative type;
c) the principle of a criteria complexity;
d) the principle of clarifying criteria.

The principles are based on the fact that when creating new products at the level of the world's best samples, the criteria should be modified in comparison with the criteria of modernization and modification, which usually have minimax (type 1) or boundary (type 2) nature.

The principle a claims that type 1 criteria can form an insignificant part, since creating a new product changes a large number of its principal parameters. Therefore, the most of criteria should be boundary (no more, no less, in the interval) and be formed based on expert evaluation.

The principle b indicates that when evaluating decisions (performed work), relative criteria obtained by comparing synthesized versions of technical systems or by comparing with a prototype (prototypes) at the advanced world level become very important.

Let us consider some examples. For instance, cost supplement by 15% does not say anything as a criterion. However, if the accuracy of measuring the parameter is increased by a factor of 2 in this case, then the parameter is acceptable.

The principle c states that the overall product evaluation must be carried out by complex criteria, criteria derivatives applied at each stage. For example, increasing product complexity, its design hierarchy is not the best case if we take into account design only.

Nevertheless, it can allow keeping to the principle of building block design while simplifying planning an industrial output, to simplify and reduce the cost of its assembly and maintenance.

The principle d determines the need for gradual criteria specification. Product design is not completely specific at the initial design stages. Therefore, expert criteria do not always have a quantitative form; they can be represented by expressions of fuzzy logic of the form “basically fulfilled requirements”, “doubtfully fulfilled requirements”, etc.

Detailing design documentation provides the transition to numerical values of criteria.

4.5. Determining a person responsible for a particular process in QCS

The question who is responsible for a particular process is important. It is difficult since various company divisions participating in it already have their leaders. Usually, the most competent division head (who understands the essence of the process) should lead the process. The task of other division heads is to distribute executives properly.

Here we get a logical, not always accepted though, distribution of leadership by a functional and administrative feature.

The leader of a lower-level process is functionally subordinated to the head of the process which includes the given one.

4.6. How to make a final decision correctly

We consider that for this purpose, all processes in the organization should be divided into two groups:

1. processes that directly affect the quality of goods;
2. processes that do not directly affect the quality of goods, but are necessary for implementing first group processes.

The first group processes in production, for example, include the processes of design preparation, technological preparation, manufacturing, testing, etc., i.e. the processes that are a part of the concept of a product life cycle.

The processes of the second group are transportation, document management, financial management, formation of contracts, etc.

Therefore, the most worthwhile way of organizing process quality assessment is the following.

The processes of the first group are the most responsible. Therefore, for them it is necessary to introduce understandable scales translating qualitative estimates into quantitative ones by attracting experts. For each process, it is necessary to define a minimal assessment boundary, below which the process must be repeated anew.

If we have estimates for each process related to product life cycle stages or steps, it is necessary to obtain a weighted (integrated) estimate of a process set that directly affect product quality.

Obviously, expert systems are necessary here since organization representatives are the experts.

For the processes of the second group, it is sufficient if a division head controls functions of a particular process within his division based on additional criteria.

Let us consider a method of decision-making based on fuzzy sets as an example [13]. A team of experts, who are company representatives, assesses possible control actions using the following method.

1. Experts are assigned with weights (their sum is equal to 1) taking into account: a) a degree of responsibility for a decision; b) a qualification in a solution domain.

2. Experts determine a permissible lower limit of their general confidence in the effectiveness of a control action aimed at ensuring product quality (recommended based on professional experience ≥ 0.7).

3. Experts determine a periodicity of adjustments (it is recommended as private assessments in QCS appear).

4. Each expert discusses and estimates an option of control impact (confidence in achieving a result by implementing the proposed control action) in numerical form (from 0 to 1).

5. Getting a weighted estimate of experts' general confidence in achieving product quality by implementing the discussed action.

6. A person responsible for making a decision makes a decision (to implement a particular decision or not).

7. Go to the next assessment point. Assessment points correspond to product life cycle stages and steps.

Another issue is a way to determine weighted confidence of all experts. For this purpose, a knowledge base based on fuzzy sets has been developed using expert estimates [13].

The rules have the following form:

(IF confidence of the expert 1 with weight P_1 is equal to A_1) AND (IF confidence of the expert 2 with weight P_2 is equal to A_2) AND ... (IF confidence of the expert n with weight P_n is equal to A_n) THEN (as a result, weighted confidence of the experts is equal to B_i).

The linguistic variable A_i has 3 terms: sufficient, mean, insufficient as shown in figure 2.

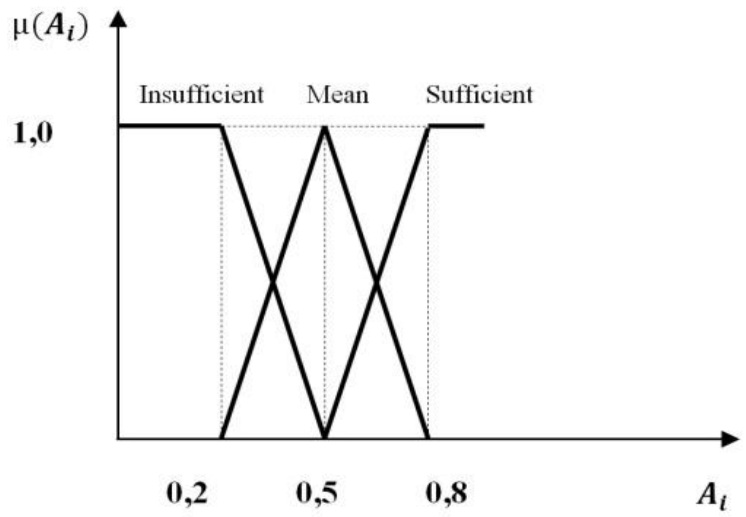

Figure 2. The membership function for the linguistic variable A_i.

The expert assessments helped to form the following fuzzy production rules that determine the value of the linguistic variable B_i (weighted confidence of experts). Preliminary in the production rule, there are mutually exclusive subconditions containing opposite values of the linguistic variable A_i (sufficient ⇔ insufficient). We can see that the result is production rules that contain only adjacent values of the linguistic variable A_i.

1. IF (all subconditions contain the value of the linguistic variable A_i – sufficient) THEN (the value of the linguistic variable B_i is very reliable).

2. IF (all subconditions contain the value of the linguistic variable A_i – insufficient) THEN (the value of the linguistic variable B_i is very unreliable).

3. IF (the number of subconditions with the value of the linguistic variable A_i – average and exceeds the number of subconditions with the value of the linguistic variable A_i – sufficient or insufficient) OR (no more than one less than the number of subconditions with the value of the linguistic variable A_i – sufficient or insufficient) THEN (linguistic variable B_i is doubtful).

The linguistic variable B_i has 5 terms: most reliable, reliable, doubtful, unreliable, and quite unreliable (figure 3).

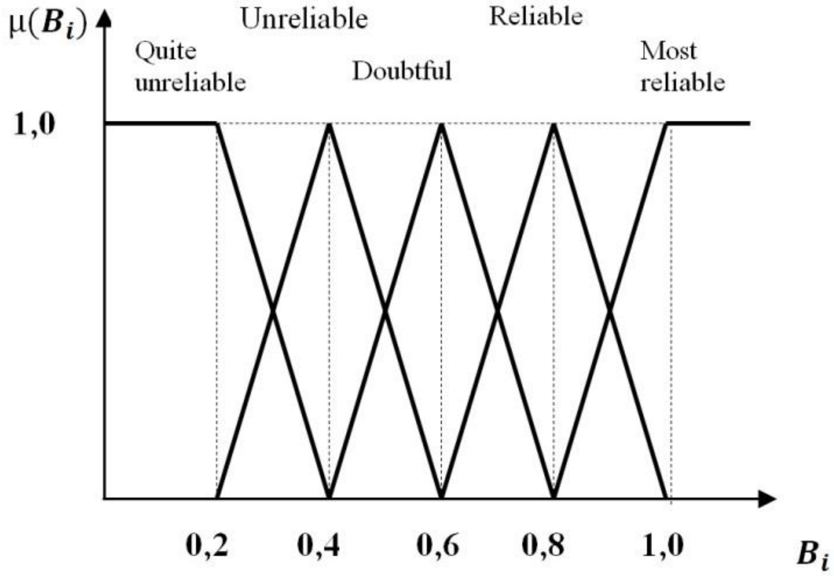

Figure 3. The membership function for the linguistic variable B_i .

4. IF (the number of subconditions with the value of the linguistic variable A_i – sufficient or insufficient more than one exceeds the number of subconditions with the value of the linguistic variable A_i – mean) THEN (the linguistic variable B_i is reliable or unreliable, respectively).

For example: (IF confidence of the expert 1 is sufficient AND confidence of the expert 3 is sufficient AND confidence of the expert 4 is average) THEN the value of the linguistic variable B_i is reliable.

The phasilogical conjunctions of subconditions are carried out according to the minimum rule.

Finding joint membership functions is usually according to Mamdani's fuzzy implication.

The defuzzification of a weighted assessment of experts' confidence (result) is performed by the centroid method.

4.7. What performers are needed when implementing quality management systems

The success of a quality management system is mostly determined by employees engaged in the activities.

It is also important that the management is ready to implement quality management systems, that is:

1) understanding that quality cannot be cheap, that it is necessary to invest in it;
2) it is necessary to invest in technical re-equipment of production;
3) it is necessary to invest in staff development.

The most difficult task is to make all process participants to understand a sense of corporate responsibility for the result. It is important to convince everyone involved in the process that the successful functioning of a company in general is the guarantee of well-being of each executive.

Experience shows that it is difficult to avoid forming an appropriate corporate culture and using methods for stimulating employees' activities, namely incentives, and not anti-incentives (punishment).

Thus, it becomes clear that the development and implementation of effective automated quality management systems makes it necessary to take a fresh look at company activities, to rethink the usual activity rules.

Practical implementation of decision-making procedures in machine-building production systems is given in [7, 8, 18].

5. Conclusion

The authors consider that the main conclusion is that quality management is a way of company functioning. Therefore, all the processes of company activities must be subordinated to the goals of this activity method. In other words, all processes of company activities should be built into a quality control process.

The opponents might say that the article is partly polemical and many statements can be objectionable. We can agree with this point of view. The paper has a conceptual nature. However, in the opinion of the author, the main problem points are indicated.

Therefore, the authors deliberately do not consider the problems of optimization of a company functional structure, its divisions, stages of work on introducing quality management systems, etc.

It is also necessary to mention that the introduction of a quality management system will seriously affect not only mid-level management units, but also the activities of top management. It will also cause silent protest and rejection of some employees.

Therefore, the effective implementation of activities related to quality control depends on the will of top management.

The proposed approach to the creation of an automated quality management system is implemented at a machine-building enterprise; the results of implementation and testing are adequate to the stated. In the near future, it will be possible to summarize them and present them in the form of publications.

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