Improvement of Methodology of End-to-End Integrated Management of Quality of Metrological Activities in Geographically Distributed Systems of Ensuring the Uniformity of Measurements

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Abstract

The article examines the place of metrological activities in geographical systems of ensuring the uniformity of measurements in terms of integrated quality management. Quality of metrological activities is a complex multidimensional object of management, where the tasks of obtaining an objective assessment of its efficiency belong to the class of poorly formalized tasks described by the availability of various kinds of uncertainties, vague limitations, incomplete and fuzzy data.

The objective of the article is to develop a methodology of end-to-end integrated management of quality of metrological activities in geographical systems of ensuring the uniformity of measurements that function under various kinds of uncertainties, vague limitations, incomplete and fuzzy data.

A conceptual model and methodology of systemic quality management were proposed, aimed at improving the efficiency of functioning of the geographical system of ensuring the uniformity of measurements within five main target subsystems "Metrological activities", "Market", "Finance", and "Resources".

A hierarchical model was developed, as well as a method of assessing the systemic management of quality of geographical system of ensuring the uniformity of measurement and its structural formations using balanced scorecard and theory of fuzzy sets, which allow to obtain an adequate assessment under uncertainties, vague limitations, incomplete and fuzzy data.

A hierarchical model of fuzzy inference was developed, as well as a method of assessing the efficiency of the systemic management of quality of metrological activities of the geographical center of standardization, metrology and testing as a structural object of the geographical system of ensuring the uniformity of measurements. This model is notable for ability of multi-level calculation of efficiency by several levels of the system: process → group of processes → quality management system, which allows to improve rapidness and objectivity of managerial decision-making in the field of systemic quality management.

Keywords: *quality management system, metrological activities, ensuring the uniformity of measurements, distributed system, fuzzy inference model, method of efficiency assessment.*

1. Urgency

Metrological activities as a process are the vital object of management in the quality management system (QMS) of any production structure. Activities of this process are aimed at ensuring the uniformity of measurements, controlling the product performance and improving the accuracy of the measuring tools in use. Its quality largely influences the accuracy of setting the control tools and conditions for the functioning of production equipment, control of the quality of purchased materials and product components, optimal saturation of production processes with measurement tools, and ultimately – the product quality (Solyanik & Kravets 2008b).

The process of metrological activities is geographically distributed in its structure, since it is closely interlinked with the regional system of ensuring the uniformity of measurements and essentially depends on the quality of its functioning. In these conditions and due to the constant growth of the stock of measuring tools, a permanent improvement of the quality of metrological activities is becoming a significant problem for businesses (Soratto et al. 2014; Roebben et al. 2010; Quality, Metrology, and cGMP/FDA Regulations). Resolution of this problem requires the development of appropriate scientific and methodological approaches to the rational use of various kinds of resources of all objects of management of the geographical system of ensuring the uniformity of measurement and methodology of end-to-end integrated quality management.

Quality of metrological activities is a complex multidimensional object of management, where the tasks of obtaining an objective assessment of its efficiency belong to the class of poorly formalized tasks described by the availability of various kinds of uncertainties, vague limitations, incomplete and fuzzy data (Gildeh & Asghari 2011). In this regard, there is a clear need for scientific research and methodological developments to form a model of managing the geographical system of ensuring the uniformity of measurement, capable to continuously maintain the high quality of metrological services at all stages of their life cycle. The incompleteness of the scientific research in this field determines the urgency of the topic, its selection and range of issues under consideration.

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2. Objective and tasks

The objective is to develop a methodology of end-to-end integrated management of quality of metrological activities in geographical systems of ensuring the uniformity of measurements that function under various kinds of uncertainties, vague limitations, incomplete and fuzzy data. The following tasks have been solved to achieve this objective:

- from the standpoint of systematic analysis, the geographical system of ensuring the uniformity of measurements has been examined in order to identify the main features and problems in the field of quality management; the necessity to develop the methodology of end-to-end integrated management of quality of metrological activities under various kinds of uncertainties, vague limitations, incomplete and fuzzy data have been justified;
- the methodology and conceptual model of managing the quality of metrological activities for geographically distributed system of ensuring the uniformity of measurements have been proposed, as well as the algorithm of its development and improvement;
- the hierarchical model of fuzzy inference of the assessment of efficiency of systemic management of the quality of metrological activities of the geographical center of standardization, metrology and testing as a basic structure of the territorial system of ensuring the uniformity of measurements has been developed and implemented; and
- the organizational and technical forms of integration of the developed methods, models and algorithms in the form of an expert system, organizational and methodological center of managing the quality in the geographical system of ensuring the uniformity of measurements have been proposed.

2.1. Analysis of the state of the problem

Analysis of the state of the problem of improving the efficiency of managing the geographical systems of ensuring the uniformity of measurements has led to the identification of the general laws of development of geographical systems of ensuring the uniformity of measurements and features of their functioning under the new socio-economic conditions. It has been shown that the system of ensuring the uniformity of measurements currently has a pronounced distributed structure. The geographical systems of ensuring the uniformity of measurements play a key role in this structure. These systems, as complex organizational and technical structures, belong to the systems of a low degree of formalization (Solyanik & Kravets 2011). Their research and modeling are associated with certain difficulties that relate to the need to reconcile the interests of various objects of management and direct their efforts at the implementation of the key objective – ensuring the uniformity of measurements and quality of metrological services in the region (Kachwala 2015; Priede 2012; Mark 2014). This objective is first of all achieved by increasing the efficiency of the system functioning and, most importantly, by managing the quality of metrological services.

2.2. Conceptual modeling of quality management

The conceptual model of quality management, general methodology of creation and development of such systems and algorithm of their practical implementation have been proposed based on the systemic analysis of the activities of regional systems of ensuring the uniformity of measurements.

Typical geographical system of ensuring the uniformity of measurements consists of the following subsystems: legal, organizational and technical. As a rule, it includes research metrology institutes, regional centers of standardization, metrology and testing, metrological services of organizations and enterprises (Thiam et al. 2009).

Conceptually, the methodology of end-to-end integrated management of quality in geographical systems of ensuring the uniformity of measurements can be represented by a complex of activities, techniques and information technology gradually integrated in the well-known cycle of W. Edwards Deming (Deming 1986) (Figure 1).

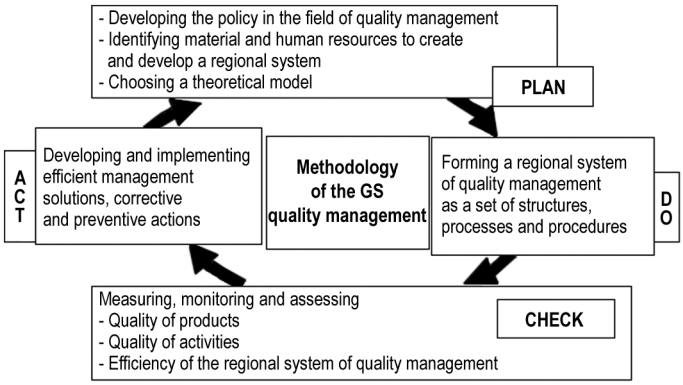

Figure 1. Methodology of quality management in geographical systems of ensuring the uniformity of measurements gradually integrated in W. Edwards Deming cycle

Out of four stages of the cycle, the first and the second stages of the cycle are elaborated well methodically. The third stage was reflected in research papers in such fields as metrology, qualimetry, statistical modeling, etc. (El-Tawil 2015). However, the methodically integral presentation of the aspects of activities under this stage was elaborated only strategically. In our opinion, the fourth stage is the key. Indeed, the management system must manage, or more precisely, generate efficient control actions (corrective and preventive actions, feedback, etc.). To date, this step lacks any detailed scientific and methodical study. Today, management is more of an art, largely determined by the personality of the head, rather than the daily work of the manager.

2.3. Algorithmization and modeling of the methodology of quality management in geographical systems of ensuring the uniformity of measurements

In accordance with the established objectives and tasks, quality management (QM) in geographical systems of ensuring the uniformity of measurements has several (at least two) control loops (Solyanik & Kravets 2008b):

- loop of “general quality management”, outlined in the form of requirements to the QMS;
- loop of “local quality management”, specific in methods, approaches and tools.

The loop of “general quality management” is a loop of the first level. The loop should provide a comprehensive approach to quality management at the level abstracted from the type of product, features of the life cycle, organizational structure, type of ownership, etc. Its scope is a network of processes forming the business; its object is issues of efficient planning, provision, management and improvement on the level of core complex managerial processes of the QMS prescribed in these sections of the standard, as well as their interaction with the processes of the life cycle. The subject of the loop is top management of the organization.

The loop of “local quality management” is a loop of the second level; the objective of the loop is to ensure the efficiency of managing the quality of both the entire business process and all of its components. The loop should provide a comprehensive approach to quality management under specific conditions de-

termined by both external and internal factors. Scope of the local QM loop is both every single process of the network of processes and business process of the organization as a whole. Subjects of the loop are responsible performers of the processes (as a rule).

It is obvious that these two loops are interconnected and subordinated to each other. As a result, quality management in geographical systems of ensuring the uniformity of measurements is a rather complicated dual-loop system of interrelated processes "servicing" the network of processes that determine the quality of the final product. The algorithm of practical implementation of the methodology of quality management in geographical systems of ensuring the uniformity of measurements is shown in Figure 2.

Analysis of the main components of regional systems of ensuring the uniformity of measurements has allowed to introduce the methodology of quality management in the form of a conceptual model that expands the model developed in (Solyanik & Kravets 2008a), and shown in Figure 3. The model unites the target subsystems and economic entities and control impacts. In the meantime, its functional side reflects the behavior of the system under control actions and external impacts, while the structural side reflects the relationship between structural elements and target subsystems.

The proposed model allows to visually unite the field of metrological management of geographical system, system of management of its structural formations and the core objectives of managing the quality of metrological activity into a single image, where classical general management functions and special management functions are located on the Z-axis of the model, representing the successive stages of the management cycle (classes of the control impacts – n). Target management subsystems are located on the Y-axis – i. The X-axis is used to display the subjects of the geographical system – j.

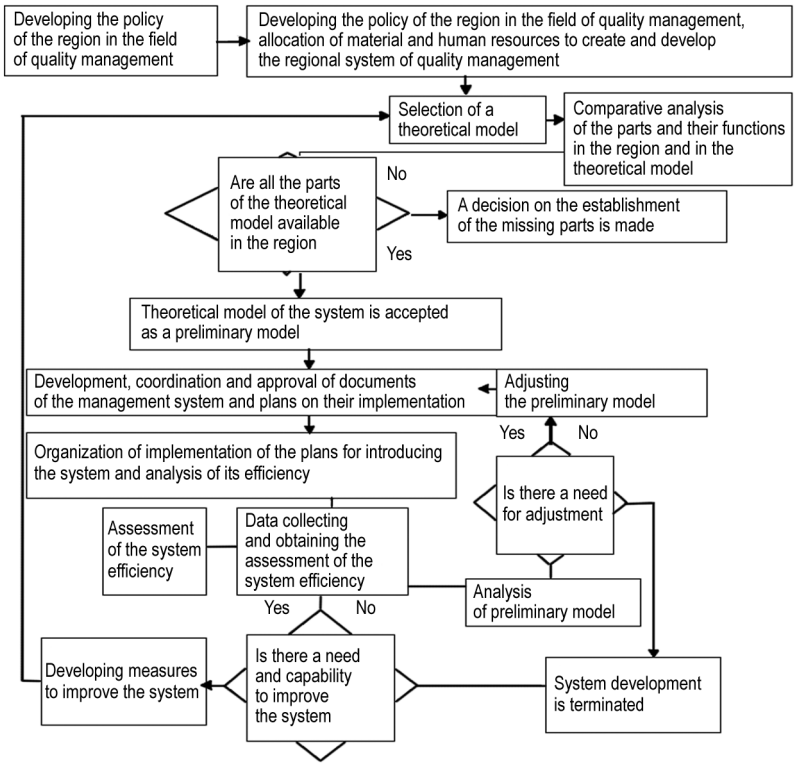

***Figure* 2. Algorithm of practical implementation of the methodology of quality management in geographical systems of ensuring the uniformity of measurements**

Examination of the problematic situation and the practice of real management of GS of ensuring the uniformity of measurements allows to determine the following target subsystems: "Metrological activities", "Resources", "Finance", "Market". These subsystems can be defined as a constant part of systems, since they are common for most of the geographical systems of ensuring the uniformity of measurements.

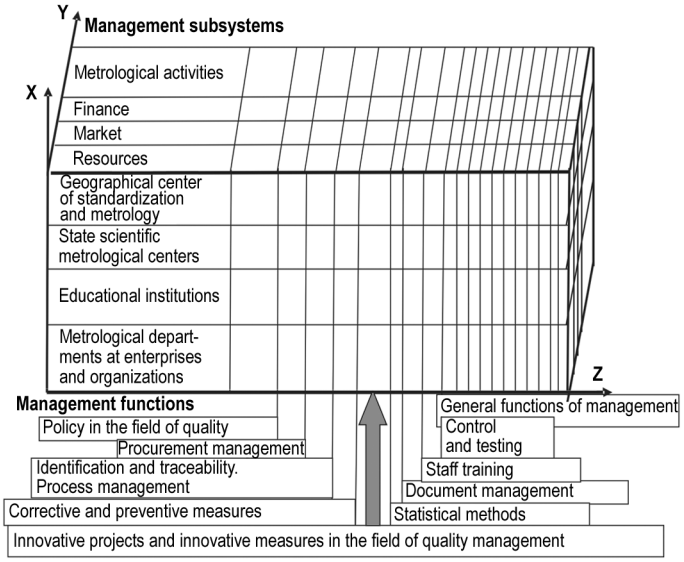

***Figure* 3. Conceptual model of systemic management of quality of ensuring the uniformity of measurements**

The method of analysis of regional socio-economic systems, proposed in (Ponomarev et al. 2005), can be used to formalize such models, where the criteria of efficiency of the system of managing the product quality are focused on additive contraction of partial quality indicators for each process. However, numerical values of the parameters, except for the core accreditation indicators, are rarely used in the geographical systems of ensuring the uniformity of measurements; the expertly formed verbal assessments are most commonly used instead of the numerical values, which greatly complicates their practical use. As a result, the subjective opinion of an expert can prevail in the assessment, which raises a number of uncertainties in the description of the system parameters and assigns the tasks of making decisions in the field of quality management to the class of poorly formalized tasks with vague limitations, incomplete and fuzzy data. Besides, as the studies showed, it is advisable to use fuzzy logic to solve such tasks.

2.4. Hierarchical model of fuzzy inference and the method of assessment of efficiency of the systemic quality management

The features of the hierarchical model of fuzzy inference and the method of assessment of efficiency of the systemic management of quality of metrological activities in the functioning of the structural objects of the geographical system of ensuring the uniformity of measurements are the following:

- ❑ strong dependence on external factors – for example, the state policy in the field of ensuring the uniformity of measurements, changing market demands, etc.;
- ❑ vague nature of regulatory documents;
- ❑ uncertainty, incompleteness of input data, which often makes it impossible to determine the consequences of decisions made; and
- ❑ solution of management tasks largely depends on fuzzy goals and decision rules.

The features above assign the task of obtaining the assessment of partial criteria (indicators) K_i, K_j, and general K in the

model under study to the class of fuzzy and poorly formalized tasks. To solve this problem, the thesis research uses fuzzy logic, while the model of assessing the efficiency of the systemic quality management considers it as a fuzzy system (FS), where the balanced scorecard (BSC) formed by the author is used as input data.

The input variables have been classified, and a directed graph of links between the aspects of the Balanced Scorecard has been built on its basis in order to build a model K_j of assessing the efficiency of the systemic quality management of the *j*-th structural object included in the geographical system of ensuring the uniformity of measurements (Figure 4).

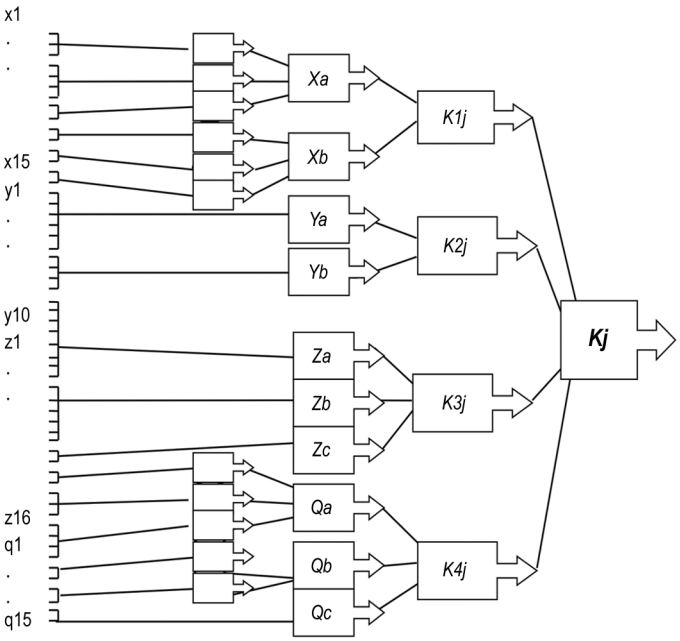

***Figure* 4. Directed graph of links between the aspects of the Balanced Scorecard**

The following aspects have been identified: $K_{1,j}$ is an aspect of resources and development; $K_{2,j}$ is an aspect describing the market (relationships); $K_{3,j}$ is finance; and $K_{4,j}$ is metrological activities. For each of the four aspects, the object is obtained with a single output and inputs of the following type:
$K_j = f_r(K_{1,j},K_{2,j},K_{3,j},K_{4,j})$; $K_{1,j} = f_x(x_1,x_2,...,x_n)$; $K_{2,j} = f_y(y_1,y_2,...,y_n)$; $K_{3,j} = f_z(z_1,z_2,...,z_n)$; where K_j is an integral indicator of the efficiency of the systemic management of the quality of the *j*- th structural object of the geographical system, $K_{1,j}$, $K_{2,j}$, $K_{3,j}$, $K_{4,j}$ are intermediate output indicators; x_i, y_i, z_i, q_i are input variables (balanced scorecard). These relationships are assigned to the fuzzy logic equations that allow to determine the level of the indicator K_j by the maximum of the membership function. Linguistic variables X, Y, Z, Q are defined to assess each of the aspects. Figure 5 shows the structure of the hierarchical model of fuzzy inference of the assessment of efficiency of the systemic management of quality of the *j*-th structural object included in the geographical system of ensuring the uniformity of measurements (PR – production rulebases).

The developed fuzzy model has a hierarchical structure, which takes into consideration the specifics of arrangement of metrological activities. It provides for the assessment both of indicators $K_{1,j}$ …$K_{4,j}$ and of the indicator K_j, which makes it possible to implement a methodology of managing the metrological activities of the geographical system of ensuring the uniformity of measurements in the form of an expert system.

3. Issues of practical implementation

The issues of practical implementation of the proposed model and its experimental testing on the example of fuzzy modeling of the assessment of systemic management of quality of the metrological activities have been reviewed. 29 criteria of assessment of systemic quality management have been identified on the basis of the expert analysis: 24 criteria relate to the assessment of 4 types of activity (initial verification, periodic verification, calibration, other works), 6 for each type of activity: assessment of the dynamics of profitability; assessment of the dynamics of the number of MT, average number of verification officers; number of MT per verification officer; dynamics of the average cost; output per verification officer.

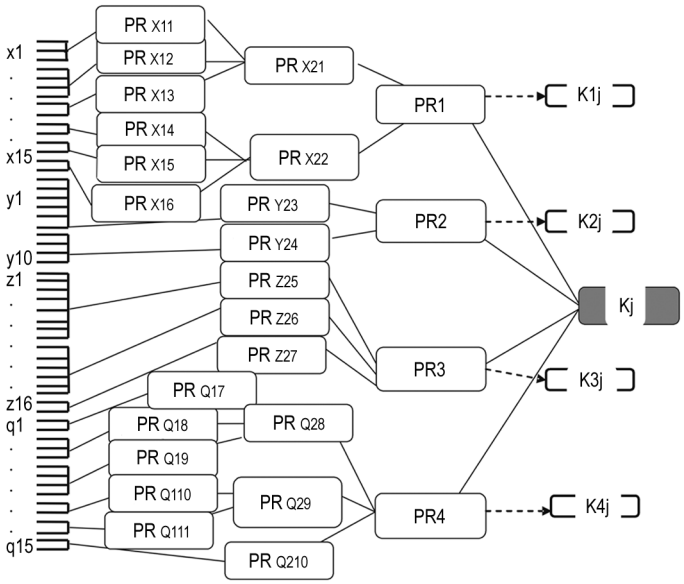

***Figure* 5. Structure of the hierarchical model of fuzzy inference of the assessment of efficiency of functioning of the *j*-th structural object included in the geographical system of ensuring the uniformity of measurements**

Rulebases of the fuzzy system were developed with the involvement of experts in the field of ensuring the uniformity of measurements.

To build a fuzzy model of assessment of efficiency of the QMS of the typical State regional center of standardization, metrology and certification, its process model has been formed, as shown in Figure 6.

Efficiency indicators for each process calculated on the basis of information from the process owners serve as the source of data for the calculation of the comprehensive assessment of the QMS efficiency. Singling out and analyzing the efficiency indicators for each process and QMS in general allow to make conclusions about the dynamics of development of the object under study and its state at any time. Membership functions can be built on the basis of the expert survey.

Since the efficiency of the QMS of the regional center of metrology is assessed by several levels (by processes, groups of processes and QMS as a whole), a hierarchical structure of the production model of knowledge representation was used.

The first level of the model is a system of fuzzy inference for assessment of the QMS state for each of the identified business processes. Efficiency is assessed at the second level by all five groups of processes. The integral indicator of QMS efficiency is assessed at the system output. Universals are made based on the actual intervals of change in the actually employed partial efficiency indicators. The output of the fuzzy model is considered as linguistic variables whose values are determined from the following term {low, medium, high}.

The obtained values of the QMS efficiency indicator generally objectively reflect its real dynamics in the last 4 years. The developed fuzzy model has a complex hierarchical structure, which is explained by the specifics of the QMS of the production structure under consideration. The system provides for assessment of the intermediate efficiency indicators by processes and groups of processes, which in turn increases the flexibility of its setting and the adequacy of the assessment, as well as allows the owners of these processes to assess their

efficiency by end results and to take appropriate managerial decisions in the field of systemic management of the quality of metrological activities on time. The structure of the proposed hierarchical model is implemented in the Fuzzy Tech environment, which allows to create multi-level systems of fuzzy inference of assessment of the systemic quality management with a high degree of particularization and to implement this methodology in the form of an expert system. The general structure of the information system of supporting the decision-making in the field of systemic management of the quality of metrological activities of the regional system of ensuring the uniformity of measurements is shown in Figure 7.

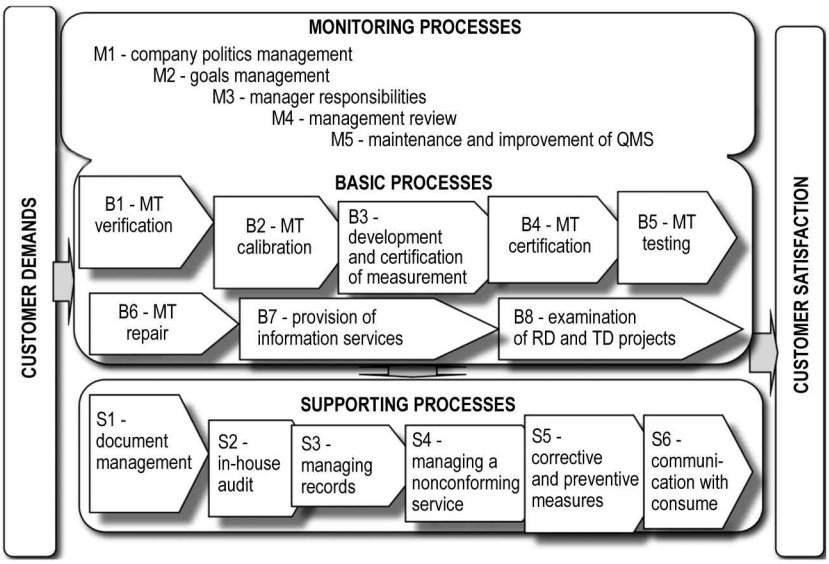

***Figure* 6. Process structure of the QMS of the regional center**

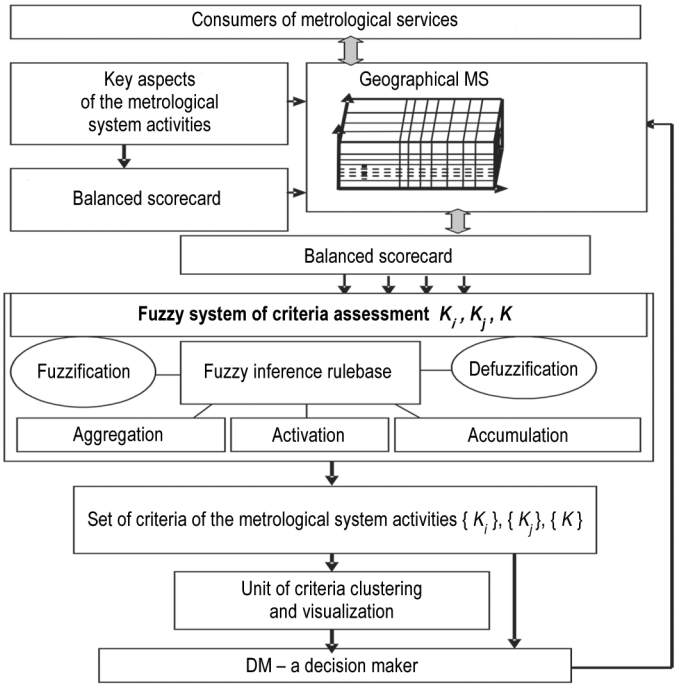

***Figure* 7. Flowchart of the expert system of managing a regional center of metrology in the aspect of the quality of its metrological activities**

The expert system is intended for quality assurance managers, managers of business processes and MS heads. In the system, a decision-maker (DM) may set the expected changes in the values of a range of indicators, determined by a choice of a certain option of the decision made or by influence of internal and external factors. An analysis of the dynamics of changes in the QMS MS efficiency allows to objectively judge the feasibility of implementing a particular innovative project associated to a systemic quality management, assess the efficiency of metrological activities carried out in the MS and make timely operational and strategic decisions on the management of the quality of metrological activities.

4. Key results

The work has solved the urgent scientific and technical task of developing the methodology of the end-to-end integrated management of the quality of the metrological activities of the geographical system of ensuring the uniformity of measurements that function under various kinds of uncertainties, vague limitations, incomplete and fuzzy data.

1. It has defined the key problems and features of the systemic management of quality of metrological activities in geographically distributed systems of ensuring the uniformity of measurements associated to the basic functional structures: organizational, economic, production and financial.

2. A conceptual model and methodology of systemic management of the quality have been proposed, aimed at improving the efficiency of functioning of the geographical system of ensuring the uniformity of measurements within five main target subsystems “Metrological activities”, “Market”, “Finance”, “Resources”.

3. A hierarchical model has been developed, as well as a method of assessing the systemic management of quality of geographical system of ensuring the uniformity of measurement and its structural formations using balanced scorecard and theory of fuzzy sets, which allow to obtain an adequate assessment under uncertainties, vague limitations, incomplete and fuzzy data.

4. A hierarchical model of fuzzy inference has been developed, as well as a method of assessing the efficiency of the systemic management of quality of metrological activities of the geographical center of standardization, metrology and testing as a structural object of the geographical system of ensuring the uniformity of measurements. This model is notable for ability of multi-level calculation of efficiency by several levels of the system: process → group of processes → QMS, which allows to improve rapidness and objectivity of managerial decision-making in the field of systemic quality management. **Q-as**

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