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Fuzzy Modeling of Quality Parameters of Higher Education in a Multicultural Environment

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Abstract

The aim of this study is to develop and test an algorithm for organizational and pedagogical actions to determine and formalize quality indicators of higher education in a multicultural environment using fuzzy logic. The Mamdani algorithm is used as a fuzzy logic tool as a systematic basis for the process of determining quality indicators of higher education. To achieve this goal, the following tasks were solved during the study: using linguistic variables, 21 parameters and 85 quality indicators were determined in various fields, including the socio-cultural one; rule bases were determined through expert analysis, which were subsequently optimized using the principles of comparing intermediate values, prioritizing larger elements, and ensuring the compatibility of results; dependency surfaces were constructed using the MATLAB software package, which made it possible to analyze input-output relationships using fuzzification, logical inference, composition, and defuzzification. The procedure for determining quality indicators of higher education in a multicultural environment using fuzzy logic developed by the authors was tested at two universities in the Republic of Uzbekistan. It has been demonstrated that this organizational and pedagogical support system provides an accurate, reliable, and detailed quality assessment that surpasses traditional methods. In practice, the university's formalized quality parameters can be integrated into an automated quality monitoring system, increasing the transparency of management decisions. The study's results may be useful to higher education institution administrators, policymakers, and quality assurance specialists in higher education, as well as researchers studying evidence-based management practices.

Keywords: quality management, objectivity, fuzzy logic, model, quality of education, Mamdani algorithm.

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Introduction

Globally, attention is being paid to the quality of higher education as a factor determining core strategy and a necessary component of competitive advantage. In the context of practical reforms to the current educational system, "quality" is becoming a topic of discussion, given the direct connection between higher education and national economies and public life. Leading global higher education institutions have adopted standard quality management models based on the ISO international standard, the European Quality Management System (EQMS), the American National Quality Award, and Australian universities based on the principles of Total Quality Management (TQM) to enhance the effectiveness of educational processes, internal communications, strategic development, and decision-making.

At the international level, particular attention is being paid to research in the areas of creating a dynamic organizational and managerial structure for quality management systems, ensuring the integrity of management cycle functions, refining the composition of control measures within the framework of the Bologna Declaration based on mutual conformity, cooperation between comparative criteria and methodologies, and the ERASMUS+ program, which aims to internationalize and reform the higher education system. The identified problems related to meeting the demands and needs of the labor market, regulatory and legal acts, international cooperation, defining perfect strategic goals inherent in a competitive environment, identifying sources of problems, monitoring the level of professional competence in educational areas and student specialties, and transparently assessing the effectiveness of teaching activities have become the object of research in the theory and practice of quality management.

Globalization processes have led to the creation of a multicultural higher education environment. The socio-academic environment of a modern university is characterized by diverse national and cultural values and behavior patterns among students and faculty. In such an environment, the educational process must be assessed not only by traditional academic results, but also by the level of cultural adaptation, intercultural communication, and social integration. Consequently, management decisions at the university must be made taking into account the socio-cultural needs and expectations of educational participants. To ensure

that these needs are addressed within the quality management system, they must be formalized, ensuring the required level of reliability and objectivity.

Today, numerous traditional methods and tools exist for collecting, analyzing, and evaluating management data in higher education, most of which focus exclusively on statistical data. Such methods are insufficient for a modern university, as they rely primarily on quantitative data and ignore the qualitative components of a multicultural educational environment. Their drawback is that they do not consider the views, opinions, or suggestions of stakeholders. To formalize the qualitative parameters of the educational environment related to socio-cultural components, it is necessary to use linguistic variables described in terms of natural language, i. e., fuzzy language. Fuzzy modeling, developing at the intersection of applied mathematics and management, is considered an effective method for accounting for socio-cultural factors in the educational environment. This type of modeling is more suitable for social spheres, including educational activities, by translating the human factor into quantitative indicators. This allows for the processing of information reflecting qualitative characteristics using the values of linguistic variables, which subsequently transforms verbal assessments into digital ones.

Purpose and objectives of the study

The purpose of this study is to develop and test an algorithm for organizational and pedagogical actions at a university to define and formalize quality indicators of higher education in a multicultural environment using fuzzy logic. The Mamdani algorithm was selected as the fuzzy logic tool. To achieve this goal, the following tasks were defined:

- to study the scientific and practical literature on the research problem;
- to determine the parameters and indicators of quality of higher education using linguistic variables and the characteristics of the university's multicultural environment;
- to use expert analysis to determine and optimize rule bases for processing quality indicators;
- to construct input-output dependency surfaces for logical inference using MATLAB;
- to test the proposed organizational and pedagogical actions to define and formalize quality indicators of higher education using fuzzy logic.

Literature review

The primary goal of fuzzy logic is to simulate human thought processes by feeding events or processes into algorithms that consist of rules such as IF "statement" THEN "result". As Pegat (2013) notes, people do

have a history of forming opinions about certain circumstances and behaving in accordance with previous beliefs based on unclear or ambiguous facts. Fuzzy modeling is based on rules representing empirical information or subject matter expertise in the problem domain (Volkova et al., 2009).

Today, fuzzy logic algorithms are becoming popular for quality assessment in various subject areas. For example, there is interesting experience using fuzzy logic tools based on the Mamdani model to assess the quality of artificial intelligence based on available data (Dusakaeva et al., 2023) and to select players for a football club during preseason training camps (Dusakaeva et al., 2022).

In the field of pedagogical research, experiments are also being conducted to evaluate elements of educational processes using fuzzy logic. Specifically, Z. Viryansky and S. Shaposhnikov used this model to assess the development of competencies in the educational process (Viryansky & Shaposhnikov, 2017). A. Mitin and T. Filicheva used it to develop information and analytical systems for monitoring the quality of educational services (Mitin & Filicheva, 2016). I. Rudinsky organized a formal structural description of the pedagogical process using fuzzy logic (Rudinsky, 2005).

The theoretical foundations for the development and practical application of a pedagogical technology for assessing the quality of education in higher education based on fuzzy modeling tools and methods are explored in the works of N.V. Ismailova (Ismailova et al., 2012).

Some studies are devoted to the use of fuzzy logic methods in the management and evaluation of scientific and innovative activities with the aim of introducing cluster approaches to the integration of education, science, and industry in the innovative development of universities (Galimov, 2019; Usmonov, 2020).

Researchers also consider it relevant to study the requirements for the development of management decision-making systems at universities, which are related to the increasing complexity of quality assessment models and changes in the socio-cultural environment (Askarov et al., 2024; Matthews, 2011; Siakas, 2007; Soloviev & Filatov, 2014).

Thus, the use of fuzzy logic in quality management in higher education is becoming increasingly necessary due to the growth of information technology and automation, the increasing complexity of social processes, and the development of cultural diversity.

Our analysis of the scientific and practical literature led us to the conclusion that there is a need to develop a decision-making support system at the university based on education quality using a fuzzy logic algorithm.

Methodology

Based on the research of A.R. Marakhimov (Marakhimov & Sapaev, 2009), the fuzzy rule of parameters related to the quality of education was expressed as follows:

$$(i): Q; P; A \Rightarrow B, (1)$$

Here (*i*) is the name of the fuzzy rule, Q is the environment for implementing the fuzzy rule, that is, the educational process; P is the condition for applying the goal of the fuzzy rule; $A \Rightarrow B$ is the goal of the fuzzy rule; A is the conditions of the goal; B is the conclusion of the goal; $\Rightarrow$ is the sign of logical sequence.

Since the basis for fuzzy inference is a rule base containing fuzzy "If – Then" statements, as well as membership functions for the corresponding linguistic terms, the following conditions were met in the study:

- there must be at least one rule that uses any term from the input variable as a requirement;
- the fuzzy inference rule base must contain at least one rule for each linguistic word from the output variable.

The inference engine went through the following four stages: fuzzification, fuzzy inference, composition, and defuzzification.

Fuzzification, based on information about clearly defined initial training parameters, yields results in determining fuzzy word meanings. Therefore, we devoted considerable attention to its verification process by stepwise defining a fuzzy quality system in terms of educational characteristics. For this purpose, we engaged specialists with experience in higher education as experts. Next, using fuzzy logic based on the Mamdani algorithm to construct linguistic variables, we determined the number of linguistic words and assigned a numerical value to each fuzzy term. In the final stage of defuzzification, which includes the process of obtaining accuracy, all processed linguistic variables were assigned an exact value. Thus, as a result of fuzzy modeling of the system, it becomes possible to numerically evaluate the output parameter of the qualitative data.

The higher education quality assessment system used in the study included 21 parameters in six areas: governance and decision-making, faculty competence, curriculum content and organization, infrastructure and technology, international cooperation, and student competence. The use of linguistic variables allowed for the identification and operationalization of 85 indicators. Twenty-two experts defined rule bases, which were subsequently optimized using principles such as intermediate value matching, prioritization of larger

elements, and ensuring consistency of results. Dependency surfaces were constructed using MATLAB software, enabling input-output relationship analysis using fuzzification, inference, composition, and defuzzification.

The algorithm and organizational and pedagogical recommendations developed during the study for fuzzy modeling of higher education quality parameters in a multicultural environment were implemented at two universities (sites) in the Republic of Uzbekistan: Termez State University and the Kattakurgan branch of Samarkand State University. The obtained results were subjected to statistical processing using the Mann-Whitney U-test and confirmed the reliability of the difference from the arithmetic mean estimates.

Results

Since the act of mathematically formalizing fuzzy data is the creation of a fuzzy set, a group of set elements will have similar characteristics to varying degrees. Therefore, what matters is how closely an element matches the fundamental properties of the set, not whether it belongs to the set (Shtovba, 2007). Assessing educational quality using fuzzy technologies requires adhering to rules for translating linguistic descriptions into strict quantitative values, such as: compatibility of intermediate values, priority of major elements, compatibility with the output element, and expert opinion. The automatic generation of rule sets for each linguistic criterion is programmed by dividing the sum of the values in the assessment sets by the average coefficient of the intermediate assessment.

We initially determined the assessment coefficient for each indicator in accordance with the linguistic criterion with the participation of experts. Using the analytical hierarchy process (Saaty, 1993), the level (weight) of the indicators was determined and, accordingly, a rule base was formed.

The next step involved optimizing the existing rule base by applying the principles of 1) intermediate value matching, 2) large element dominance, 3) output element matching, 4) homogeneity reduction, and 5) expert opinion.

Next, using the Fuzzy Logic Toolbox in Matlab (MATLAB 6.5), changes in the optimal dependence surfaces were detected, indicating the influence of input variables on the value of the output variable (Figure 1).

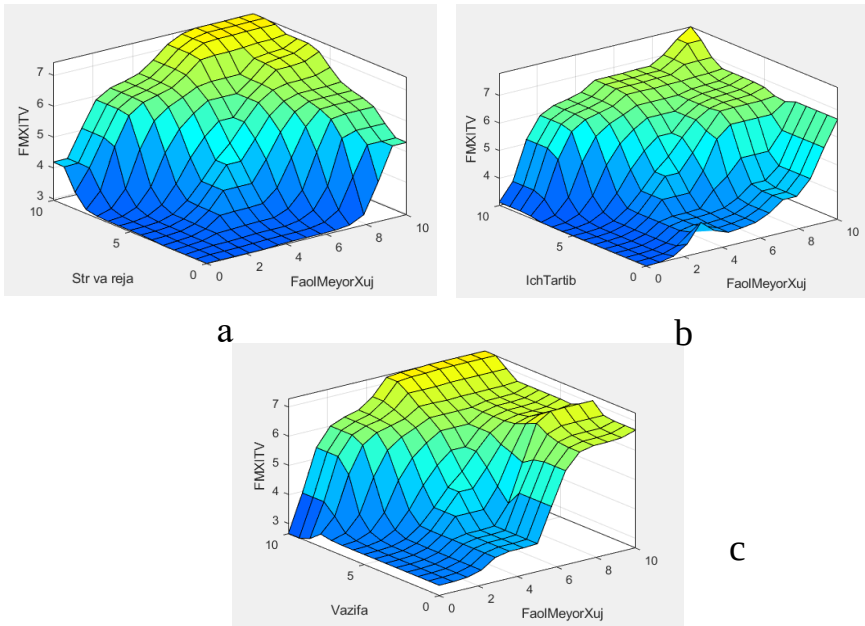

Figure 1. Optimal dependency surfaces indicating the influence of input variables on the value of the output variable (for example, one parameter)

Using this model, it is possible to determine the parameter indicator, for this it is enough to enter the values of the corresponding indicators in the "Data verification Window" obtained within the framework of the university's quality monitoring system (Figure 2).

Figure 2. Data verification Window

Thus, the following areas of the internal education quality monitoring system at the university were identified: 1) regulatory framework for governance and decision-making quality; 2) quality of faculty potential and professional development; 3) content and relevance of instruction, quality of organizational processes of educational activities; 4) level of material and technical resources, infrastructure, and technological support; 5) quality of international cooperation; 6) level of students' knowledge, professional training, and recognition.

Next, 21 quality parameters and 85 indicators were identified, which allowed for a separate assessment and generalization of quality control areas. Their selection, based on strict assignment, serves the systematic implementation of control processes based on timely improvement of the efficiency of collecting, processing, storing, and disseminating information, stages of education, or the state of its individual components.

Based on the described approach, a set of 28 models was developed that clearly and simply illustrate the stages of the process structure, revealing its composition, interrelations, and interdependencies. These models help understand the internal organization of the process, enable the assessment of the parameters of each area, and, based on their results, provide an objective assessment of the overall state, which can then be used to formulate conclusions for management decisions.

The approaches used in the study were subjected to expert evaluation, which found the developed linguistic descriptions and outcome assessment criteria, evaluation indicators, and results to be acceptable.

For expert evaluation of the quality assessment model, a questionnaire consisting of six sets was compiled, and a corresponding ratio was obtained from a group of 22 independent experts. The results were applied to 28 models developed during the study based on fuzzy methods for assessing pedagogical objects, and the quality level of the assessed objects (universities) was determined. As a result, the overall quality index for the first object was 6.63, and for the second, 6.07 (Table 1).

Table 1. The results of the inclusion of indicators in fuzzy logical models in the experimental work processes.

Parameter	1-object	2-object
I. The regulatory framework of management, the quality of decision-making	7,69	7,35
II. The quality of the potential and professional development of the teaching staff	7,11	6,72
III. The content and validity of training, the quality of organizational processes of educational activities	7,04	6,84
IV. The level of material and technical base, infrastructure, technological support	7,52	6,14
V. The quality of international cooperation	7,02	4,2
VI. The level of knowledge, professional training of students and recognition	7,54	7,54

The accuracy and reliability of the indicators identified using fuzzy models were studied by comparing them with the values determined by the arithmetic mean method, the Mann-Whitney U-test method was used. Here, the correctness of the results is checked provided that U_{emp} is not greater than $U_{amp}(U_{emp} < U_{emp}(0{,}05), U_{emp} < U_{emp\text{кр}}(0{,}01))$.

At the first object, it was determined that U_{emp}=146, U_{amp}=207 ($p \leq 0.05$) and 174 ($p \leq 0.01$), and at the second object U_{emp}=169.5, U_{amp}=207 ($p \leq 0.05$) and 174 ($p \leq 0.01$), in both objects the condition $U_{emp} < U_{amp}$ is fulfilled. This showed the importance of the difference between samples, indicators on fuzzy logic models differ from arithmetic averages.

Discussion

While classical logic often uses a single type of logical implication, fuzzy logic utilizes a variety of these implications. These include the fuzzy implications of Gödel, Mamdani, Łukasiewicz, Gogen, Wadi, Brouwer, Aliev, and Sugeno, fuzzy implications based on the production formula, the fuzzy implication R-SEQ R-SE, and others (Leonenkov, 2003). We agree with some authors (Marakhimov & Khudaibergenov, 2019; Mukeshimana, 2019) who believe that Mamdani and Sugeno fuzzy systems are currently the most commonly used varieties. The knowledge base in systems such as Mamdani consists of rules such as "If x1 = low and x2 = medium, then y = high". The knowledge base of systems like Sugeno consists of the following rules: "If x1 = low and x2 = medium, then y = a0 + a1x1 + a2x2". Clearly, the methods for assigning output variable values are where Mamdani and Sugeno systems differ most. The advantage of Mamdani-type models is that the knowledge base rules are explicit and understandable, but for Sugeno-type models, it is not always obvious which linear input-output relationships should be used. Therefore, the use of the Mamdani model in our study was justified. However, in our future studies, it will be interesting to try applying the Sugeno model to the analysis of education quality indicators in a multicultural environment.

Processes based on fuzzy technologies are regularly automated using various methods. Educational systems also devote considerable attention to modeling performance evaluation procedures using software packages designed for creating and studying complex systems (Bocharnikov, 2001). Following this approach, we also used the Fuzzy Logic Toolbox module of Matlab (MATLAB 6.5) to construct optimal dependence surfaces showing the influence of input variables on the value of the output variable. This package allows for the creation of expert systems based on fuzzy logic, clustering using fuzzy algorithms, and the design of fuzzy neural networks. At the same time, we agree with Tumanov (2014) and believe that constructing an optimal model requires significant effort for subsequent fitting, where much depends on the rule system. On the one hand, the more rules, the more accurate the resulting picture is. On the other hand,

rule redundancy should be avoided, as there is a high risk of becoming confused by a huge list, which will undoubtedly complicate the modeling task.

Conclusion

The Mamdani algorithm, considered a systems approach and a method of fuzzy logic theory based on university quality control parameters, has high potential for developing a fuzzy model for assessing the quality of the organization and implementation of educational processes.

Our study showed that the university should implement a decision support system consisting of four stages of organizational and pedagogical activity:

- In the first stage, with the participation of experts, an assessment coefficient is determined in accordance with the linguistic criterion for each indicator of a multicultural educational environment;
- In the second stage, with the help of experts, the priority of the indicators in relation to a given parameter is determined;
- In the third stage, a database of existing rules is formed, that is, sets of assessments $\{x_{ij}\} = a_i * b_j, i = \overline{1,n},\ j = \overline{1,m})$ are calculated, corresponding to indicators sorted by priority value according to the linguistic criterion;
- In the fourth stage, the existing database of rules is optimized. To achieve this, we use the correspondence of intermediate values, the predominance of major elements, the correspondence of the output element, and the sequence of expert opinion conditions.

In particular, the implementation of abstract inference mechanisms takes into account the characteristics of a multicultural educational environment. Education quality indicators are refined using linguistic variables. The analysis of educational processes and the university's systems as a whole is carried out using a systems approach and fuzzy logic methods, ensuring an objective assessment of educational quality in a multicultural university environment.

We believe that our proposed organizational and pedagogical recommendations for supporting management decisions using fuzzy logic methods ensure the reliability and accuracy of the higher education quality parameters defined in the university's internal monitoring system.

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