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COGNITIVE MODELING OF UNIVERSITY MANAGEMENT SUPPORT AS A HUMAN-MACHINE SYSTEM

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Abstract

On the example of a university, the article discusses the possibilities and features of using a cognitive approach for modeling weakly (fuzzy) structured ergatic (human-machine) systems and their management. A methodology for constructing and analyzing a cognitive model of educational institution management based on fuzzy cognitive maps is proposed and investigated. Solutions based on the use of mathematical and software tools of the decision support system (DSS) “IGLA” on fuzzy models are described. The results of their application in the tasks of management support and modeling of weakly (fuzzy) structured organizational, technical, and ergatic systems are discussed.

New approaches to the study of fuzzy information objects and results are outlined. The study develops a methodology for increasing the structural level of the university management model, including the management of all three missions of the university: educational, research, and social.

The research materials presented in the article can be useful for studying the dynamics of complex organizational and technical systems. The article addresses scientists, university professors, graduate students, and undergraduates.

Keywords: system of systems, ergatic system, decision support systems, soft model, weakly structured system, cognitive modeling, fuzzy cognitive map, structural and target analysis, scenario analysis, visualization.

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КОГНИТИВНОЕ МОДЕЛИРОВАНИЕ ПОДДЕРЖКИ УПРАВЛЕНИЯ УНИВЕРСИТЕТОМ КАК ЧЕЛОВЕКО-МАШИННОЙ СИСТЕМОЙ

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Аннотация

На примере университета в статье рассматриваются возможности и особенности использования когнитивного подхода для моделирования слабо структурированных (нечетких) эргатических (человеко-машинных) систем и управления ими. Предложена и исследована методология построения и анализа когнитивной модели управления образовательным учреждением с помощью нечетких когнитивных карт. Описано использование математических и программных средств системы поддержки принятия решений (СППР) «ИГЛА», базирующейся на нечетких моделях. Обсуждаются результаты их применения в задачах поддержки управления и моделирования слабо структурированных (нечетких), организационно-технических эргатических систем.

Обрисованы новые подходы к исследованию нечетких информационных объектов. В статье разработана методика повышения уровня структурированности модели управления вузом, которая охватывает все три функции университета — образовательную, исследовательскую и социальную.

Материалы исследования, представленные в статье, могут быть полезны для изучения динамики сложных организационно-технических систем. Статья адресована ученым, преподавателям вузов, аспирантам и студентам.

Ключевые слова: система систем, эргатическая система, системы поддержки принятия решений, мягкая модель, слабо-структурированная система, когнитивное моделирование, нечеткая когнитивная карта, структурно-целевой анализ, сценарный анализ, визуализация.

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1. Introduction

Digitalization of all aspects of life and activity of modern society could not but affect the educational sphere. The introduction of elements of artificial intelligence into the university management and education requires close interaction between a person and a robot assistant. Hybrid intelligence is being formed on the basis of a well-proven “human-machine” system. At the same time, computers are being given increasing importance in the implementation of all three missions of the university: educational, research, and social. Obviously, according to H. A. Simon, such a system is classified as weakly structured [1, 2]. From the perspective of experts, some of the parameters of this system can be described quantitatively while others can be described qualitatively. Additionally, the subjectivity of the description characterizes a certain measure of structure [3]. In accordance with state standards¹, this system has to be classified as an ergatic (ergotechnical) system with hybrid intelligence. In other words, the ergatic system “person—information” is formed in the process of operators carrying out practical activities during intellectualized human-information interaction.

It is quite logical to formalize the structure of such an ergatic university management system in the form of an intelligent decision support system (DSS) and to model it during the study based on a cognitive approach.

The purpose of the article is to develop a methodology for increasing the level of structure of the university management model, including the management of all three missions of the university.

2. Analysis of existing approaches to intelligent decision support tools

Management decision support systems are also known as DSS. Their development and operation are aimed at providing decision makers with comprehensive information about the state of the analyzed object (organization, division, product, financial instrument, etc.) and the external environment in which this object operates. The result of this provision is a set of solutions — actions that transform the properties of the object under study to ensure its long-term effectiveness in the context of target indicators (such as profitability, liquidity, payback, etc.).

¹ GOST R 43.4.1-2011 Information support for equipment and operator activities. System “Person — Information”. (In Russian.) <https://files.stroyinf.ru/Data2/1/4293787/4293787774.pdf>

There is a set of DSS classifications. So, **according to the method of influencing the decision-making process, they are divided into:**

- **active:** are designed only to provide the decision makers with an operational cross-section about the state of the object under study;
- **passive:** can model alternatives to balance the risks of adopting an option as a target;
- **combined:** suggest interaction in which a specialist or the Planning, Learning, and Resource (PLR) management staff can adjust the options offered by the system for optimization reasons, thereby contributing to further training of the system and improving its efficiency.

According to this logic, DSS are divided into:

- **communicative:** this type of system involves the collective work of several specialists or decision makers on the development of a solution;
- **informational:** focused on the collection and processing of data, including time series. They are implemented in the form of internal corporate DBMS (Database Management Systems);
- **documentary:** focused on processing the flow of internal and external documentation of various formats;
- **intelligent:** have learning functions based on solving similar problems in previous periods;
- **modeled:** designed for the development of scenarios (models) for specified target conditions.

For clarity, we present this classification in the form of a diagram in Figure 1.

On the classification shown in Figure 1, the second block of varieties is of the greatest interest, namely, intelligent and simulated DSS, since they not only support the decision maker with an up-to-date information slice but also provide recommendations for choosing one or more alternatives to the original set of solutions.

In the construction of DSS, special attention is also paid to the **methodological basis on which the system builds its work in evaluating alternatives**. Therefore, **the following methods are known:**

- **regression and variance analysis:** modeling the behavior of the resulting indicator (dependent variable) as the input arguments (independent variables) of the resulting function (regression equation) change. In practice, a linear relationship is established between the input arguments and the value of the resulting function. The least squares method is used to express it;
- **multidimensional and discriminant analysis:** based on training functions, the initial set of alternatives is divided into related groups. Un-

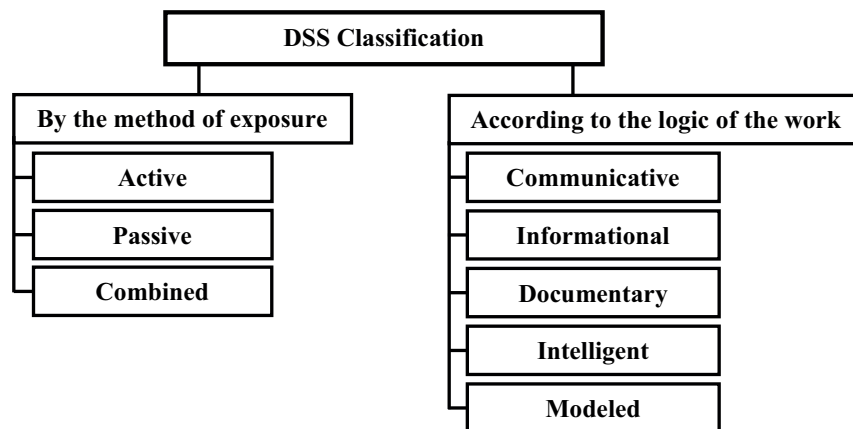


Fig. 1. The DSS classification

like cluster analysis, here, the rules for forming groups are known and set in advance;

- **time series analysis:** historical statistics are decomposed into composite indicators and their changes are predicted using algorithmic (simple and weighted moving average) and analytical (predictive extrapolation by growth curves) methods. If the nature of the change in indicators is seasonal or cyclical, then an analysis of periodic fluctuations or a spectral analysis of a time series is carried out. The time series themselves are divided by the type of dynamics into stationary (without a clear trend) and non-stationary (with a trend). In this regard, the methodological basis of time series research is expanding due to special methods for stationary series:
 - MA-models (moving average);
 - AR-models (autoregressions);
 - mixed models (ARMA);
 - ARIMA models (integrated moving average and autoregression);
- **survival analysis:** the study aims to determine the duration of the process from the moment of its beginning to the end, with the last event being a random variable, and the first being clearly defined in time. The subject area of such research is quite wide (for example, in medicine — life expectancy after surgery, immunity resistance after vaccination; in personnel management — work experience studies; in trade — product life cycle studies, etc.). The method is based on the use of survival tables (Kaplan—Meier method) as well as the Cox regression model, which allows not only to estimate the duration of the process but also to identify external factors that bring its completion closer and assess the degree of their influence on the process;
- **factor analysis:** similar to the previously applied survival analysis, but offers less knowledge-intensive research tools, such as chain indexes and coefficients. The most common example of factor analysis is the DuPont equation, which shows the dependence of the return

on equity of an enterprise on a number of characteristics (production efficiency, efficiency of asset use, etc.).

In general, the task of decision making is reduced to a sequential narrowing of the set of available alternatives to the target ones. The process is multi-iterative [1] and at each iteration is accompanied by a refinement of the target criteria.

At the same time, as already noted, it makes sense to recommend as many alternatives as possible in order to balance the risks of choosing one of them. In risk management, this approach is called diversification and provides the solution object with an optimal and predictable change over time.

In the case of a discrete assignment of selection criteria, the final selection is limited, and, consequently, the risks of choosing a target alternative from the resulting set also increase. Alternatives that are not included in the target set established by the PLR or by a specialist within the margin of error are missed. In this regard, the efficiency of DSS based only on the above methods decreases.

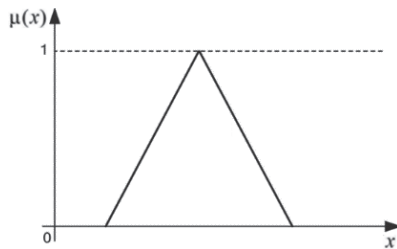
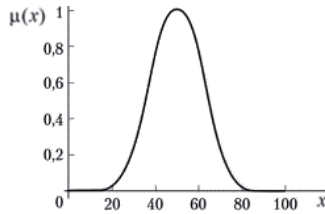
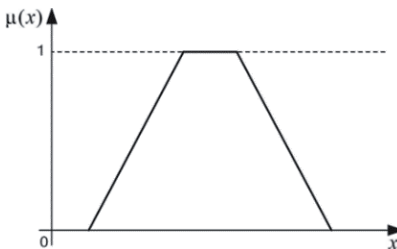
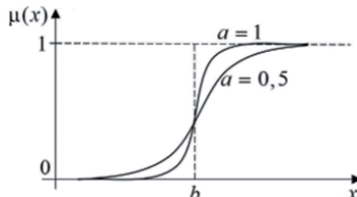
It is possible to **significantly increase the efficiency of DSS by including fuzzy-oriented methods based on the mathematical apparatus of fuzzy set theory in the logic of its operation**. Their implementation makes it possible to take the task of selecting target alternatives from the original set to a new level of abstraction by adding the concept of “degree of belonging”.

With the help of membership functions of known types, the degree of occurrence of an alternative in a given target set determined for acceptable estimates of an alternative according to decision making criteria is estimated (see Table 1).

As can be seen from Table 1, the degree of belonging is characterized by a value in the range [0; 1]. Different types of functions are suitable for classifying belonging to sets defined by phrases from artificial or natural languages. For example, triangular functions are used to assess compliance with the requirements of the “average value” type, bell-shaped — for “about”, trapezoidal — for “range of values”, sigmoid — for “more than” or “less than”.

Table 1

Types and descriptions of accessory functions

Name of Function	Type of Function	Description of Function
Triangular		$\mu(x) = \begin{cases} 0, & x \leq 0 \text{ OR } x \geq c \\ \frac{x-a}{b-a}, & a < x \leq b \\ \frac{c-x}{c-b}, & b < x < c \end{cases}$
Bell-shaped		$\mu(x) = \exp\left[-\frac{(x-b)^2}{2c^2}\right]$
Trapezoidal		$\mu(x) = \begin{cases} 1, & b < x < c \\ 0, & x \leq 0 \text{ OR } x \geq d \\ \frac{x-a}{b-a}, & a < x \leq b \\ \frac{d-x}{d-b}, & c < x < d \end{cases}$
Sigmoid		$\mu(x) = \frac{1}{1 + \exp[-a(x-c)]}$

Measures (weighted Hamming distance, Euclidean and Mahalanobis measures, etc.) are used to determine the distance between the evaluation of an alternative by the i^{th} criterion and a vaguely defined target set (requirement). The degree of importance (significance) of the criteria is determined on the basis of weighting coefficients empirically deduced by an expert or by a computational method (Saati's method of hierarchical analysis).

The permissible error ratio (sensitivity) is also set for inclusion in the general package of recommendations of alternatives that do not fully meet the target sets of requirements. Currently, there is one known fuzzy benchmarking system [2] that implements this approach.

3. Cognitive approach to the study of complex systems

When modeling systems using the cognitive approach, it is common to combine various models under the term “cognitive modeling”. This approach

investigates the structure of the system as well as its functioning and development processes. One effective type of cognitive model is V. B. Silov's fuzzy cognitive maps (FCM) [4].

A variant of this model type represents the system being modeled as a weighted oriented graph. The vertices correspond to the factors or concepts describing the system, and the arcs correspond to the causal relationships between them. Each arc has a weight that characterizes the intensity of the corresponding influence [4]. Currently, there is an interest in software support for cognitive models. An overview of a number of existing cognitive modeling software systems is presented in [4, 5]. Among these tools, the authors identified the IGLA decision support system, which allows to automate the construction of V. B. Silov's FCM to a large extent, “to perform their structural-target and scenario analysis”, and on this basis “to search and simulate control actions to bring the system under study to the desired target state” [6]. This software system, implemented as a Windows application to provide data exchange, implements the functions of importing

and exporting cognitive models and builds reports on the results of cognitive modeling [6, 7].

In modern management practice of organizational and socio-economic systems having the properties of System of Systems [8], a decision-maker usually has to work with poorly structured management tasks and decision-making situations with a set of NON-factors [9].

Among the reasons for this situation, we can note the incompleteness of information about the state of the system in an insufficiently controlled and dynamic external environment.

The uncertainty caused by subjective reasons is not limited to the lack of sufficient knowledge about the system to make management decisions. It also arises from the complexity of the relationship between the goals of the development of socio-economic systems and the formation of criteria for evaluating management decisions. According to [10], it is common for management subjects to recognize dissatisfaction with the current state of the system, but its ideas about the causes and possible solutions are often blurred, fuzzy, and contradictory. Formalizing these representations is a crucial task in developing models and decision-making methods for poorly structured systems and situations.

A cognitive map is called “a causal network that reflects a subjective (individual or collective) researcher’s idea of the system in the form of a set of semantic categories called factors or concepts and a set of causal relationships between them” [12].

Thus, a FCM is a sufficiently effective tool for, at least, the evaluative analysis of the situation, allows identifying trends related to its characteristics and development as well as detecting significant factors influencing these processes. There is an opportunity to search and generate effective solutions for managing the system, identifying risks, and developing strategies to reduce them [13].

The cognitive model is an effective tool for exploratory, evaluative analysis of the situation. It does not allow us to obtain accurate, quantitative characteristics of the system under study. As noted in [13], knowledge of a rough, perhaps even hypothetical model of the system allows predicting scenarios for the development of situations under different control actions by changing the variables of the model.

The purpose of constructing and analyzing FCM is to solve the following main tasks [14]:

1. Identification of factors characterizing the simulated system and its environment.
2. Identification of intra-system causal relationships that take place between these factors in the process of functioning of the system under study and the effects from external factors on the components and on the system as a whole.
3. Construction of a directed graph of a causal network combining these factors and the relationships between them.

At the same time [15], the system under study is described by a finite set of factors and causal relationships (CR) [16] between them.

Factors can express both *relative* (qualitative) and *absolute* (measurable) characteristics of the system. Factors are associated with state variables expressed within a certain scale determined by the hierarchy level. Among the factors are:

- targeted;
- managed;
- observed;
- external.

CR can be *positive* if an increase in the value of the state variable of the concept-cause leads to an increase in the value of the state variable of the effect factor, or *negative* if an increase in the value of this variable leads to a decrease in the value of the effect factor.

CR are characterized by the power of influence, which, in general, can be both constant and dynamic.

There are three types of system states: initial, current, and target, each of which can be described by a corresponding fuzzy vector, the components of which are the states of its factors.

The belonging of the model to a particular state can be estimated by means of fuzzy benchmarking [17].

Fuzzy cognitive modeling distinguishes between control and external influence (EI), which is a fuzzy vector of influences on a subset of controlled factors. The set of components is finite since the number of controlled factors is finite and even less than their total number. External impact is a vector of impacts on a subset of external factors.

Typically, two types of analysis are applied to the constructed cognitive model: static and dynamic [15].

Within the framework of structural-target (static) analysis, the following tasks can be solved:

1. Identification of factors that have a significant impact on the target concepts and the system as a whole as well as factors that are most sensitive to the influence of the system as a whole and other individual factors. This makes it possible to determine the points of the most effective application of control actions.
2. Identification of stable subsets of factors that together have a significant impact on the system as a whole, allowing us to find and investigate complex control actions that simultaneously affect many factors.
3. Finding positive and negative feedback cycles.

Dynamic analysis of the cognitive model involves the study of options for the development of the system, including:

- modeling of self-development scenarios without outside interference;
- modeling of controlled development scenarios.

4. Cognitive model of regional university management

To improve the effectiveness of the university’s education quality management system, the methodology of cognitive modeling can be applied as a human-machine system. Cognitive modeling has proven to be

Table 2

Initial data for modeling

No in order	Factor	Type	Targeted	Group
1	Fame	Managed	–	Control factors
2	Prestige	Managed	+	Control factors
3	Yield	Ungovernable	+	Control factors
4	Competitors	Ungovernable	–	Control factors
5	Number of students	Managed	+	Control factors
6	Taxes	Ungovernable	–	Control factors
7	Cost of education	Managed	–	Control factors
8	Inflation	Ungovernable	–	Control factors
9	Material and technical base	Managed	–	Control factors
10	The level of digitalization of education	Managed	–	Control factors
11	Teacher qualification	Managed	–	Control factors
12	Management qualification	Managed	–	Control factors
13	Availability of hostel	Managed	–	Control factors
14	Governmental support	Observable	–	Control factors
15	Continuity of education	Observable	–	Control factors
16	Transparency	Ungovernable	+	Indicators

very promising in the development of fuzzy, poorly structured, and poorly formalized systems [18].

Cognitive modeling allows a more detailed understanding of the system under study, the identification of patterns, and the creation of more accurate models [11]. The tools and software mechanisms used for constructing and analyzing are described in detail in [12, 13]. The constructed model allows:

1. To identify the factors that have the greatest impact on the entire system as a whole and to develop indicators of the quality of education and criteria for their assessment, which will ensure the achievement of the established goals.
2. To increase the efficiency of processes in the simulated system, optimize them by changing the parameters of the control chains isolated from this model and affecting the functioning of the structure.
3. To investigate the structure of the system and to get a forecast of its behavior when finding optimal management strategies.
4. To predict the state of the system in time and conduct an assessment of the current situation.
5. To confirm that the management structure is built correctly.
6. To assess the possible consequences of decisions and determine whether these decisions can destabilize the system and “what qualitative changes will occur in concepts after these decisions are implemented” [18].

As a result of the analysis of the subject area under consideration, 16 factors (concepts) affecting the qual-

ity of education at a regional university were identified (Table 2) [2].

To build a cognitive model of the university's education quality management system as a human-machine system, the IGLA software package¹ was used. Let's take a closer look at the use of cognitive modeling based on the IGLA software package in relation to the three-component model of university management (educational, research, and social). To do this, we will form, in addition to 15 factors affecting the management of the university, three groups of indicators, the significance levels of which (in accordance with those adopted in the system of monitoring the quality of education by the Ministry of Science and Higher Education of the Russian Federation [19]) are shown in Table 3.

Together with the main management factors, the indicators recorded by the Ministry of Science and Higher Education of the Russian Federation form the concepts of the cognitive model presented in Figure 2.

Based on the use of these concepts, a fuzzy cognitive matrix was constructed (Figure 3) characterizing the connectivity of the main concepts, including positive (indicated in red) and negative connections (indicated in blue).

The given matrix corresponds to a fuzzy graph, which can be weighted, while its edges can be described using a technique that implements the method of analyzing hierarchies of T. Saati [11, 20].

¹ DSS IGLA. <http://iipo.tu-bryansk.ru/quill/manual.html> (In Russian.)

Table 3

Groups of university management modeling procedures

Control factors	Basic concepts taken into in the models account	Levels of significance in university monitoring
Indicator: Educational mission	Indicator: First mission	0,55
Indicator: Scientific research	Indicator: Second mission	0,30
Indicator: University and society	Indicator: Third mission	0,15

5. Conclusions

The article describes the experience of using soft research methods technology based on fuzzy benchmarking software, fuzzy cognitive models in solving practical problems of managing socio-economic systems [7], in particular the university, as a human-machine system, including:

- strategic management of educational, research, and socio-innovative mechanisms of the university;
- modeling strategies for managing the development of an educational institution.

In general, the use of soft and cognitive approaches in modeling poorly structured socio-economic systems

allows us to detect hidden relationships and relationships between factors that have a diverse impact on the dynamics of functioning and development, to identify factors that most affect the solution of management tasks or do not have any noticeable impact on them.

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№	Название концепта	Тип концепта	Целевой	Группа	Описание концепта
1	Fame	Управля...	<input type="checkbox"/>	Control factors	
2	Prestige	Управля...	<input checked="" type="checkbox"/>	Control factors	
3	Yield	Неуправл...	<input checked="" type="checkbox"/>	Control factors	
4	Competitors	Неуправл...	<input type="checkbox"/>	Control factors	
5	Number of students	Управля...	<input checked="" type="checkbox"/>	Control factors	
6	Taxes	Неуправл...	<input type="checkbox"/>	Control factors	
7	Cost of education	Управля...	<input type="checkbox"/>	Control factors	
8	Inflation	Неуправл...	<input type="checkbox"/>	Control factors	
9	Material and technical base	Управля...	<input type="checkbox"/>	Control factors	
10	The level of digitalization of education	Управля...	<input type="checkbox"/>	Control factors	
11	Teacher Qualifications	Управля...	<input type="checkbox"/>	Control factors	
12	Management Qualification	Управля...	<input type="checkbox"/>	Control factors	
13	Availability of hostel	Управля...	<input type="checkbox"/>	Control factors	
14	Governmental support	Наблюда...	<input type="checkbox"/>	Control factors	
15	Continuity of Education	Наблюда...	<input type="checkbox"/>	Control factors	
16	Transparency	Неуправл...	<input checked="" type="checkbox"/>	Indicator. Uni...	
17	1 mission	Неуправл...	<input checked="" type="checkbox"/>	Indicator. Ed...	
18	2 mission	Неуправл...	<input checked="" type="checkbox"/>	Indicator.Sci...	
19	3 mission	Неуправл...	<input checked="" type="checkbox"/>	Indicator. Uni...	

Fig. 2. A screenshot of DSS IGLA: Concepts of the cognitive model of university management

	Fame	Prestige	Yield	Competitors	Number of students	Taxes	Cost of education	Inflation	Material and technical base	The level of digitalization of education	Teacher Qualifications	Management Qualification	Availability of hostel	Governmental support	Continuity of Education	Transparency	1 mission	2 mission	3 mission
► Fame	0	1	1	-1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1
Prestige	1	0	1	1	1	0	1	0	1	1	1	0	0	1	1	1	1	1	1
Yield	1	1	0	0	1	1	-1	0	1	1	1	0	1	1	0	0	1	1	1
Competitors	0	0	-1	0	-1	1	-1	0	1	1	-1	0	1	1	1	1	1	1	1
Number of students	1	1	1	1	0	1	-1	0	1	1	0	0	-1	0	1	1	1	1	1
Taxes	0	0	-1	-1	-1	0	1	0	-1	0	0	0	0	1	0	0	0	0	-1
Cost of education	-1	-1	1	1	-1	1	0	0	1	1	1	1	1	1	0	1	1	1	1
Inflation	0	0	-1	1	-1	0	1	0	-1	-1	-1	0	0	0	0	0	-1	-1	-1
Material and technical base	1	1	0	-1	1	0	0	0	0	1	1	0	0	0	1	1	1	1	1
The level of digitalization of education	1	1	1	0	1	0	1	0	0	0	1	1	0	0	1	1	1	1	1
Teacher Qualifications	1	1	1	-1	1	0	1	0	1	1	0	1	0	0	1	1	1	1	1
Management Qualification	1	1	1	-1	1	0	0	0	0	0	1	0	0	1	1	0	1	1	1
Availability of hostel	1	1	1	-1	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1
Governmental support	1	1	0	-1	0	-1	0	0	0	0	1	0	0	0	0	0	1	1	1
Continuity of Education	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Transparency	1	1	1	0	1	0	0	0	1	1	1	0	1	0	0	0	1	1	1
1 mission	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2 mission	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3 mission	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 3. A screenshot of DSS IGLA: Fuzzy cognitive matrix of the university management model

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