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Generalized models of a production system of fuzzy conclusion

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Abstract. The aim of the research is to study the models, rules, and fuzzy inference engines, which occupy the main place in the knowledgebase, and models of the logic inference engines and simulation modeling, focused on supporting the adoption of semi-structured decisions under uncertainty. This implies the relevance of the task of developing theoretical and methodological tools that provide automation of the processes of fuzzy inference systems. Research methods are the theory of fuzzy sets and fuzzy logic. New scientific results are the design and formation of a set of production rules from a given set of admissible ones, with specific values of conditions and conclusions for describing three types of fuzzy models of the processes and tasks under study. Using modules of standard algorithms and programs, algorithms and a program for solving problems of fuzzy inference systems and making semi-structured decisions based on the constructed fuzzy logic model were developed. This problem is solved by formalization methods based on the theory of algorithmization, fuzzy sets, and fuzzy inference.

1 Introduction

The main provisions and principles of the proposed concept of constructing an algorithmic fuzzy inference system are as follows [1]:

- a systematic description in the chosen formalism language and an ordered presentation of the main concepts, paradigms; models, methods, and laws that describe the weakly formalized processes under study and related tasks;
- formalized representation of typical shells of problem models of a fuzzy inference system in the form of constructs of rules and fuzzy inference engines;
- ordered representation of the rules for constructing, modifying, updating, replenishing, and checking the correctness of models of production rules and a fuzzy inference system;
- a systematic presentation of typical algorithms and software modules that implement standard procedures for generating models of production rules and a fuzzy inference

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system, solving problems of a fuzzy inference system, and supporting the adoption of semi-structured decisions;

- the modularity of the structure of the fuzzy inference algorithmic system in the form of a functionally complete set of interacting algorithmic banks that automate the corresponding procedures of the fuzzy inference system and support the adoption of semi-structured decisions;
- interactive communication of the fuzzy inference algorithmic system with an expert at the stages of setting aims and conditions for the tasks to be solved, analyzing current results, and correcting them;
- automatic interaction of algorithmic banks of the system at the stages of solving the problem in a computational experiment.

The first position of the concept provides for the use of the alphabet and grammar of formalism languages used to describe the basic concepts on procedural objects of the studied weakly formalized processes and problems of making semi-structured decisions in monitoring and managing them. These objects include basic concepts, models, and methods of fuzzy logic and fuzzy sets, fuzzy graphs and Petri nets, fuzzy inference and decision making, set-theoretic models of fuzzy situations and regularities in the dynamics of their measurement under the influence of various influences, models and methods for evaluating fuzzy situations and predicting the dynamics of their development, patterns, and methods for making fuzzy decisions and fuzzy control.

In systems of fuzzy inference, decision-making, and control, languages such as Fuzzy Control Language (FCL) [2] have become widespread. The notations of this language, together with the notations of the Unified Modeling Language(UML) [3], can be successfully used in developing an algorithmic fuzzy inference system.

The second provision defines a formatted description of model shells of fuzzy inference operation, such as implications, compositions, mechanisms, and production systems based on them in the form of fuzzy logic constructs. Production systems are used for modeling and solving problems of the fuzzy inference system in the Fuzzy environment of the language tools of the fuzzy modeling program [4].

The third provision assigns the fuzzy inference algorithmic system with the properties of adaptation and solving the possibilities of solving problems when changes occur in conditions, situations, and goals (the appearance of new and the removal of some obsolete types and data). To do this, in the algorithmic system of fuzzy inference, the rules for constructing models of production systems, reflecting the specific values of the state, aims, and objectives of the fuzzy inference system, and the rules for their modification, replenishment, updating, and checking their adequacy in the event of appropriate changes in the subject field under research [5].

Following the fourth provision, in the fuzzy inference algorithmic system developed, algorithms and program modules are formed for shell designs of typical, tested, and used in fuzzy modeling and inference problems. Combining them into an appropriate sequence, algorithms and programs for solving specific problems of fuzzy inference and decision-making are synthesized [6].

Like any system, an algorithmic fuzzy inference system should consist of functional subsystems that are interconnected and united by a system-defined aim. Therefore, according to the fifth provision, the modularity of the fuzzy inference algorithmic system is presented as interconnected algorithmic banks(in the general case, of eight banks). Six of them are designed to perform the main procedures for the formation of specific models, algorithms, and programs for solving the problems of the fuzzy inference system under study, and two are for concretizing the values of conditions and aims of the tasks and managing the solution process: a computational experiment, analysis of current results and corrections (modifications, additions, updating) of initial conditions, models, algorithms, and programs for solving problems [7].

The sixth and seventh provisions stipulate, on the one hand, the interactivity of connections between the expert and the algorithmic fuzzy inference system at the initial stage and during the analysis of current results, and on the other hand, the automatic mode of operation and interaction of the six main algorithmic banks in the process of solving problems [8].

Taking into account the basic provisions and principles of the concept of constructing an algorithmic system of fuzzy inference, the proposed work explores the mechanisms for constructing a fuzzy logical model, which consists of a set of production rules, developed algorithms, and a program for constructing three types of fuzzy inference models. Algorithmic systems of this class make it possible to formalize and automate the stages of building a fuzzy logic model along the chain: experience - laws - problems - mathematical models - algorithms - programs - computational experiment - analysis of results and return through the feedback loop to the appropriate stages for corrections.

2 Methods

The conceptual model of the fuzzy inference algorithmic system reflects the most general properties of its functional modules and the schemes of their interaction. This model is represented as a set of conceptual models of algorithmic banks, characterized, as a rule, by the content of only the names of the corresponding methods, data, and messages.

In general, this model is presented in the following form [7-10].

$$AS_{FIS} =< \{M_{AB}(F_i)\}, M_{AB}(T), M_{AB}(C) > \qquad (1)$$

where $\{M_{AB}(F_i)\}$, $i=\overline{1,6}$ are the models of the main algorithmic banks, F_i is the set of functions implemented by algorithmic banks, $M_{AB}(T)$ is the model of algorithmic banks for setting tasks that forms a specific current task, $M_{AB}(C)$ is the model of algorithmic banks that controls the process of functioning AS_{FIS}.

One of the main functional algorithmic banks is the fuzzy inference system, the model of which is presented in the following form [8, 9].

$$M_{AB-FIS} =< A, L_0, L_1, P_0, P_1, P_D^0, P_D^1, R(P_D^0), R(P), R(P_D), R(F) > \qquad (2)$$

where A- the finite alphabet –is the set of identifiers of conditions and inferences in the used linguistic statements (L) and production rules (P); L_0 is the current or initial set L; $L_{П}$ is the set of admissible and possible sets L for the given problem area (task); P_0 is the current (initial) set P; $P_{П}$ is the set of admissible and possible P; P_D^0 is the current (initial) set of strategies (fuzzy inference engines) for searching and generating solutions D; $P_D^{П}$ is the set of admissible and possible strategies for searching and forming solutions D; $R(P_D^0)$ are the rules for choosing the current search strategy D from the set P_D^0; $R(P)$ are the

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rules for modifying and replenishing the current set P_0 by correcting and replenishing it with the rules from $P_П$; $R(P_D)$ are the rules for modifying and replenishing the current search strategy P_D^0 by correcting and replenishing it with the rules from the set $P_D^П$; $R(F)$ are the rules for modifying the FIS model by expanding the alphabet, correcting and replenishing sets $L_П$, $P_П$ and $P_D^П$.

The set P in the model M_{AB-FIS} can be conveniently represented by a tabular model of the following form [9, 10].

$$P_L = < A, P, Q > = < (A, B, M_A, M_B, P, F, G_A, G_B) > \quad (3)$$

where $\mathrm{A} = (A, B, M_A, M_B)$ is the finite alphabet used to describe the set of admissible states of the studied subject field and actions in solving the corresponding decision-making problems [11-14]; $A = \{A_i\}, i = \overline{1,m}$ - is the set of conditions considered as coordinates of state vectors (data vectors); $B = \{B_r\}, r = \overline{1,k}$ is the set of inferences (or their identifiers) considered as coordinates of action vectors; $M_A = \left\| a_{ij} \right\|, i = \overline{1,m}, j = \overline{1,n}$ is the compliance matrix of elements of data vectors to production rules; $M_B = \left\| b_{rj} \right\|, r = \overline{1,k}, j = \overline{1,n}$ or $j = \overline{1,n+1}$, if there are additional rules like E = <-, otherwise B_{n+1} >, meaning that if none of the rules is applicable P_j, $j = \overline{1,n}$ under conditions $A = \{A_i\}, i = \overline{1,m}$, then the actions determined by the conclusions of the vector $B_{n+1} = \left\{ b_{r,n+1} \right\}$ should be performed; $P = \{P_j\}, j = \overline{1,n}$ is the set of production rules of the corresponding type (direct, inverse); $Q = \{F, G_{A,} G_B\}$ is the set of additional parameters that characterize some properties of the rules P_j; for example, such as vector F - coefficients (of frequencies) of applicability P_j or E ($F = \{f_j\}, j = \overline{1,n}$ or $j = \overline{1,n+1}$ when there is rule E), which in a certain sense reflect their reliability or power factor; vectors GA, GB are the coefficients of the complexity of computation of A_i and B_r. The set Q is used to form strategies for searching for solutions. It can be replenished with such parameters as logic relationships between conditions, priority values of production rules, and other parameters.

Considering algorithmic banks as a large generalized object, we present its conceptual model using the notation of object-oriented technology in the following form [10].

$$M_{AB}(F_i) = < F_i, D_i, Q_i > \quad (4)$$

where: $F_i = \left\{ f_{ij} \right\}$ is the set of functions of algorithmic banks, *i,j* are the numbers of types of algorithmic banks and their functions; $D_i = \left\{ d_{ik} \right\}$ is the set of data in the *i*-th algorithmic bank, *k* is the number of types of algorithmic banks data; $Q_i = \left\{ q_{il} \right\}$ is the interface of the *i*-th algorithmic bank, *l* is the number of message types in the interface.

The hierarchical structure of the object model of algorithmic banks is represented as

$$MAB(F) = <\Pi = \{K = \{KlOi = \{O_{ij} = \{o_{ijk}\}\}\}\}> = <F, D, Q>.$$

This model reflects the hierarchy O ⊂ KlO ⊂ K⊂ Π – of the sets of objects (O), classes of objects (ClO), complexes (C), and packages (P). The sets F and D form the operational and informational parts of the AB, respectively. They are defined by attributes, procedures, and rules that reflect the general properties of the structure of algorithmic banks. Therefore, it is called the structure model of algorithmic banks [12-17].

3 Results and Discussion

Three types of fuzzy models have been developed that are described using fuzzy inference rules [13, 14].

1. Fuzzy model in the form of a nonlinear connection

$$\bigcup_{p=1}^{k_j}\left(\bigcap_{i=1}^{n} x_i = a_{i,jp}, \text{ with weight } w_{jp}\right) \rightarrow y_j = b_{j_0} + \sum_{h=1}^{H}\left[b_{j_{(h-1)n+1}}\left(x_1\right)^h + \ldots + b_{j_{hn}}\left(x_n\right)^h\right].$$

2. Fuzzy model in the form of a linear dependence

$$\bigcup_{p=1}^{k_j}\left(\bigcap_{i=1}^{n} x_i = a_{i,jp}, \text{ with weight } w_{jp}\right) \rightarrow y_j = b_{j_0} + b_{j_1}x_1 + \ldots b_{j_n}x_n .$$

3. Fuzzy model in the form of fuzzy term output

$$\bigcup_{p=1}^{k_j}\left(\bigcap_{i=1}^{n} x_i = a_{i,jp}, \text{ with weight } w_{jp}\right) \rightarrow y_j = r_j, j = \overline{1, M}.$$

For the comparative analysis, we took the known model problems located at the electronic address: *http://www.ics.uci.edu/~mlearn/databases/*. These include the following tasks: Iris Data Set, Glass Identification Data Set, Pima Indians Diabetes, Ecoli Data Set, Haberman's Survival Data Set, the task of determining the variety of wine (Wine Data Set), the task of determining the state of the liver[18-20].

For comparison, Table 1 shows the results of solving some model problems based on various known and proposed algorithms.

Table 1. Results of the proposed and existing algorithms

Task	Proposed algorithm	GBC	SGF	SVM	1NN	KNN	Conventional RBF network
Glass	88.57	83.85	74.81	72.12	71.87	71.96	68.84
Iris	99.10	97.00	96.93	98.21	95.98	94.89	94.90
Wine	97.91	100.00	98.88	98.99	94.93	95.97	96.00

In the considered fuzzy logic model (3), conditions $A = \{A_i\}, i = \overline{1,m}$ in the rules $P_j, j = \overline{1,n}$ describe a fuzzy logic-semiotic model of the set of possible states of reference situations $S = \left\{\overline{S}_{um}, \overline{S}_{ан}, \overline{S}_{ab}\right\}$ of the problem area under study [1,2], and the inferences

$B=\{B_r\}, r=\overline{1,k}$ describe a fuzzy model of action-decisions $D=\{D_{rj}\}, r=\overline{1,k}$, $j=\overline{1,n}$ [1,3] necessary to transform the current situation to the required target. The sets A and B are formed from some finite sets of values in terms of conditions and inferences.

The constructed fuzzy model of fuzzy inference systems is considered adequate, i.e., semantically correct, if with the actions from the finite set $B=\{B_r\}, r=\overline{1,k}$ any initial state is taken $\bar{s}\in\bar{S}_0$ from the set of admissible target states $\bar{S}_0$.

The correctness of a fuzzy logic model is determined by the non-contradiction and completeness of its production rules.

Consider the rules for checking the correctness of a fuzzy logic model for its simplified version, namely, for the case when the set of condition values $A_i=\left\{\overset{0}{a}\right\}, i=\overline{1,m}$ takes two values, i.e., $A=\{0,1\}$ In the general case, models with multivalued conditions $A_i=\left\{\overset{+}{a}\right\}$ can be reduced to models with two-digit values using composition operations [12-14].

4 Conclusion

The proposed concept allows one to construct models of algorithmic fuzzy inference systems that reflect the most general properties of their main functional modules and their interaction schemes. Based on these concepts and the proposed principles, three types of fuzzy logic models were built, algorithms and programs were developed, a computational experiment was conducted, and a comparative analysis of the results obtained was carried out. Such models are represented as a set of conceptual models of algorithmic banks, characterized, as a rule, by the content of only the names of the corresponding methods, data, and messages.

In the future, research will be carried out on setting the parameters of a fuzzy logic model based on neural networks and bee swarm algorithms, increasing the constructed model's adequacy. As a result of this setting, the resulting model acquires intelligent characteristics.

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