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# The Application of Hybrid Intelligence Systems for Dynamic Data Analysis

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*Abstract—The paper presents the results of scientific research, which were carried out under the set goal and solve the urgent task of developing and improving methods, models, and information technologies for assessing the states of complex spatially distributed objects based on evolutionary interval fuzzy models. A hybrid model for evaluating spatially distributed objects is proposed, which integrates developed fuzzy color Petri nets, models of deterministic, stochastic, and fuzzy knowledge bases, and the logic of manifestation of their interaction. The development allows increasing the probability of making decisions while reducing the dimension of the model by expanding the color function and the function of displaying spatial data. Alternative methods and tools for operational analysis in information technologies for assessing the states of complex spatially distributed objects have been introduced. This made it possible to reduce the influence of the subjective factor on the assessment results and increase the reliability of decisions made while reducing the time spent.*

**Keywords—**fuzzy logic; membership functions; hybrid model; colored Petri nets; evolutionary interval fuzzy model; dynamic data.

## 1. Introduction

An important aspect of making preliminary operational assessments of the state of spatially distributed objects is the lack of initial data about them. Many factors influence the object, the assessment and analysis of which is a difficult problem because of the lack of a priori data [1]. These include the multidimensionality, diversity, and multi-criteria of the set of existing factors [2], functioning under the conditions of the uncertainty of the fuzzy state space. A significant contribution to the creation, development, and research of information technologies was made by works [3]-[5], a significant breakthrough toward soft computing and fuzzy logic is the work of L. A. Zadeh [6], K. Zhang [7], and L. H. Tsoukalas [8].

The development of methods, models, and information technologies that allow, based on knowledge of oriented technologies, to implement the processes of assessing the states of complex spatially distributed objects [9] is urgent.

Analysis of publications on this topic [10]-[12] showed that the issues considered have not enough researched; scientific results are not in all cases brought to practical implementation and require additional study. This confirms the relevance and importance of the theoretical and practical results implemented in the work.

The object of research of this work is the processes of assessing the states of complex spatially distributed objects. The subject of the research is methods, models, and information technologies for assessing the states of complex spatially distributed objects.

The purpose of this work is to increase the reliability of the decisions made based on the development of a model, methods, and information technologies in the problems of assessing the states of spatially distributed objects.

The proposed model, methods, and information technologies should be focused on increasing the reliability of the decisions made.

To achieve this goal, the following key tasks are solved:

– Research of existing approaches and methods for assessing the states of spatially distributed objects based on evolutionary algorithms (Section 2);

– Development of a hybrid model of processes for assessing the states of spatially distributed objects (Section 3);

– Development of modified methods of tuning and training membership functions based on multivalued interval logic in knowledge-oriented technologies (Section 4).

## 2. Research of Existing Approaches and Methods for Assessing the State of Spatially Distributed Objects Based on Evolutionary Algorithms

Based on a meaningful analysis of methods for assessing complex spatially distributed objects [13], which are characterized by spatial and functional distribution [14], asynchronous interaction of processes represented on the set of “condition-action” relations [15], it is determined that there is a set method for assessing the states of such objects. These include deterministic, stochastic, expert, hierarchies, as well as methods of multi-criteria optimization, fuzzy sets, fuzzy Petri nets, and fuzzy logic [16].

We have established that the existing methods are object-oriented and their efficiency depends on the subject area. Assessment of the states of such objects is an important problem [9]. However, the requirements for increasing the reliability in severe constraints on computing resources and the specifics of the subject area have caused the creation and research of such models.

Let's consider the formal aspects. Let there be a set of interacting dynamic spatially distributed objects

$$\{O_i\} \supseteq \{O_i^A\},\ i \in I\ , \tag{1}$$

where $O_i^A$ is a tuple of actual objects; $I$ – a set of object indices.

When objects interact (1), a complex distributed asynchronous interaction of dynamic processes occurs

$$\{Pr_{ij}\}, i \in I,\ j \in J, \tag{2}$$

where $J$ is a set of indices of processes that can be deterministic $D$, stochastic $P$, fuzzy $\tilde{F}$, while they are often indefinite and contradictory.

Processes (2) reflect data $D_t$, and knowledge $K_n$ about the subject area. We represent their complex asynchronous interaction on the set of relations "condition $(C)$" – "action $(A)$":

$$R(CD_t, AD_t)\ , \tag{3}$$

$$R(CK_n, AK_n)\ . \tag{4}$$

Based on the peculiarities of the subject area of research, we build knowledge-oriented model $\tilde{S}_\Sigma$ for the set (1), considering the nature of the processes (2) of the interaction of objects in the set (1).

With importance for the subject area of spatial characteristics that change in time, we should focus solutions on modern geoinformation technologies [9], which allow performing spatial and temporal referencing of objects, solving distributed problems.

Of the complete set of processes occurring in the system, it is possible to represent by geoinformation technologies

$$\{Pr^{(GIS)}\} \subseteq \{Pr_j\}\ . \tag{5}$$

Considering (2), processes in objects (1) can be represented by deterministic $D$, stochastic $P$, and fuzzy models $\tilde{F}$. When evaluating objects of the subject area, one should consider many factors $\{\Phi_i\},\ i \in I$, functioning in a fuzzy state space [2].

Summarizing the above, we can conclude that the development of alternative model, methods, and information technologies for assessing the states of spatially distributed objects will increase the efficiency and reliability of decisions.

## 3. Development of Hybrid Models of Processes for Assessing the States of Spatially Distributed Objects

Within the framework of this work, a hybrid decision-making model was got [9], [17] (Fig. 1).

The hybrid model is built based on the extension of the function of colored predicate Petri nets and the function of displaying spatial data [14].

$$S_1 = \left\langle \tilde{P}, \tilde{T}, \tilde{F}, \tilde{M}_0, m_S, O, \tilde{M}_{0C}(f), \tilde{M}_C(f), \tilde{C}, \tilde{V}, \tilde{K}, L\{x_u\} \right\rangle, \tag{6}$$

where $\tilde{P}$ is a set of fuzzy positions; $\tilde{T}$ – set of fuzzy transitions; $\tilde{F}$ – fuzzy incidence function – $\tilde{F}:\left(\tilde{P}\times\tilde{T}\right)\cup\left(\tilde{T}\times\tilde{P}\right)$; $\tilde{M}_0$ – vector of fuzzy initial marking of fuzzy positions; $m_S$ – weights, which are assigned to the input $\{p_i(in)\}$ and output $\{p_i(out)\}$ arcs of some transition $t_i$; $O$ – spatially distributed component of the set of displaying coordinates $O = \langle X, Y, Z\rangle$ in geographic information systems (GIS); $\tilde{M}_{0C}(f)$ – vector of the initial marking; $\tilde{M}_C(f)$ – vector of the current marking; $\tilde{C}$ – marker color function, defines, in this case, the color $C$ of each of the markers $\tilde{M}(\tilde{p}_j)$ for grid positions; $\tilde{V}$ – conditions for making transitions depending on the color of the marker; $\tilde{K}$ – the capacity of markers in positions considering $\tilde{C}$; $L\{x_u\}, u \in U$ – some predicate, which is assigned on the model to a set of positions, transitions, incidence function in the state space of fuzzy interacting processes and defining additional conditions for performing transitions.

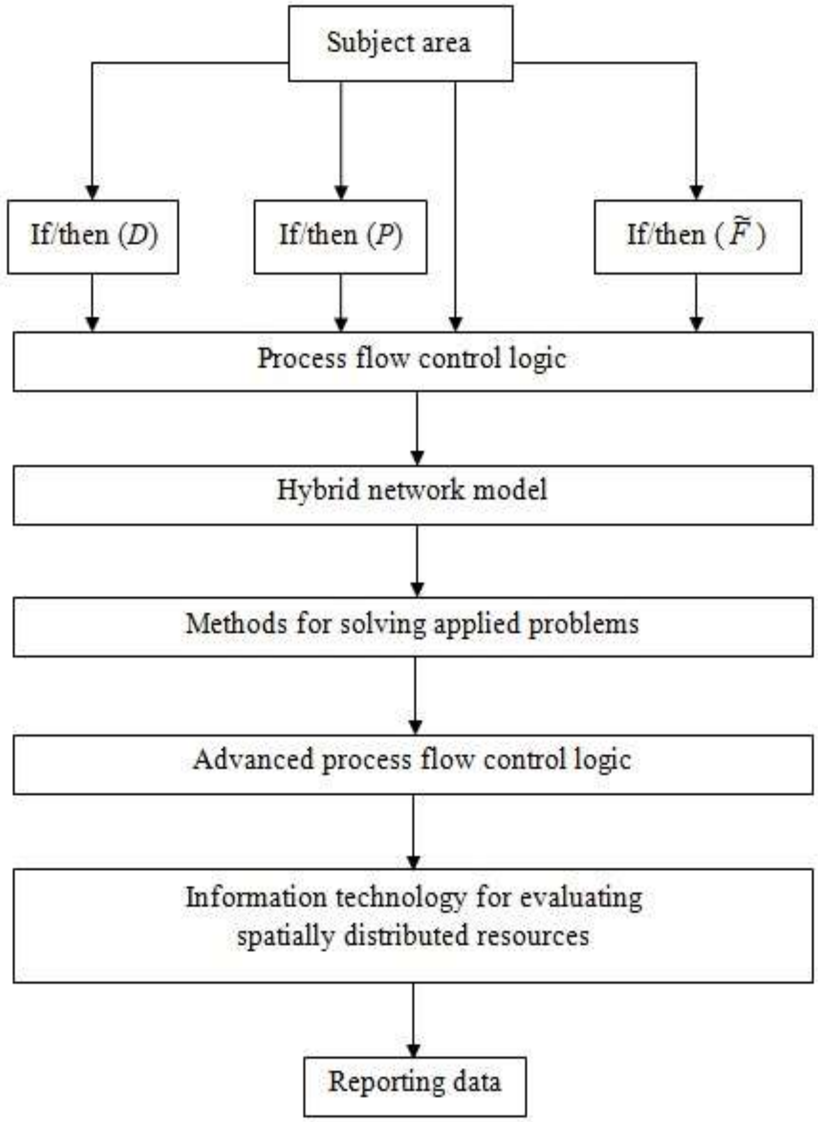


**Figure 1:** Hybrid decision-making model

Considering the expediency of reflecting a set of other important components characteristic of a certain subject area, let us expand model (6) by introducing the following quantities: sets of fuzzy positions $\tilde{P}$, fuzzy transitions $\tilde{T}$, fuzzy incidence function $\tilde{F}$, fuzzy color function $\tilde{C}$. Fuzzy marking vector $\tilde{M}_0$ is set under the membership function $\mu(x)$, $\mu(y)$, linguistic terms. When implementing $O = \langle X, Y, Z \rangle$, the application of the color function $C$ significantly reduces the dimension of the model [18]. Sometimes, it is possible to use interval logic $\Delta\mu(x)$ and its analytical forms as a membership function [13], [14].

We implemented fuzzy inference based on the Zadeh-Mamdani approaches with subsequent defuzzification [19]

$$y'_0 = \vee x'_0 \wedge \mu(x, y), \quad (7)$$

where $y'_0$ is the resulting vector; $x'_0$ – input vector; $\mu(x, y)$ – fuzzy Zadeh-Mamdani relation; $\vee$ – value finding operator $\max$; $\wedge$ – value finding operator.

So, we have proposed a new hybrid model (6) for assessing the states of complex spatially distributed objects (1), which integrates developed fuzzy color Petri nets, models of deterministic, stochastic, fuzzy knowledge bases, and the logic of their interaction

$$S_{\Sigma} = \bigcup_{k \in K} \{S_k\},\ k \in K\ , \tag{8}$$

where $K$ is a set of indices related to the hybrid model; $\bigcup_{k \in K}$ – a merge operation, which in this case reflects some additional functionality, with a display of the types of interacting processes. This allows you to vary the dimension of the model and make full use of the full range of types of characteristics of databases and knowledge in analysis tasks.

Introduction of some knowledge that is deterministic $D$, stochastic $P$, and fuzzy $\tilde{F}$ as a knowledge base model

$$S_1 = if\ /\ then(D),\ S_2 = if\ /\ then(P),\ \tilde{S}_3 = if\ /\ then(\tilde{F}) \tag{9}$$

allows you to use in analysis tasks the entire completeness of the regulatory framework, stochastic and fuzzy characteristics of the knowledge base if we take as model $\tilde{S}_3$ the production model in fuzzy representation $\tilde{F}$ in the problems of fuzzy inference Zadeh-Mamdani (Sugeno).

Based on the peculiarities of the subject area of research, the knowledge-oriented model for the set (1) has the form

$$\tilde{S}_{\Sigma} = \cup\{S_k\},\ k \in K,\ if\ /\ then - D, P, \tilde{F}\ , \tag{10}$$

and considers the determinism of the object, stochastic characteristics, and indices of fuzziness.

If the model (6) is given and some $m_{i\alpha}$ are defined, where $\alpha$ is an element of the set $A$ of existing alternatives $Alt_{\alpha}$, then the alternative $Alt_{\alpha} \in \{Alt_{\alpha}\}$ can be defined as

$$\sum m_{i\alpha} \xrightarrow{\Omega} extr\ , \tag{11}$$

$$\Omega = \langle \tau_i < \tau,\ L_i = true,\ F_i = F^*,\ m_{i\alpha} = m^*,\ O = true \rangle, \tag{12}$$

where $\Omega$ – some restrictions; $\tau_i$ – time of implementation of the alternative; $\tau^*$ – allowable time for implementing alternatives; $L_i$ – the set of predicates of the subject area; $F_i$ – set of restrictions of the subject area; $F^*$ – set of valid values of the subject area; $O$ – set of rectangular coordinates; $m^*$ is the lower limit of the allowable values of weights, which directly follows from the essence of the set of alternatives $\{Alt_{\alpha}\}$ and the current restrictions.

The conditions of reachability and consistency of processes are based on the analysis of the permissibility of transitions and the execution of predicates related to the subject area.

## 4. Development of Modified Methods of Tuning and Training Membership Functions Based on Multivalued Interval Logic in Knowledge-Oriented Technologies

In the research course, we have developed a method for modeling sequential-parallel processes of spatially distributed objects and improved the method for adjusting the parameters of the membership functions of fuzzy knowledge bases.

We base the development on multivalued interval logic, which makes it possible to reduce the computational complexity and time of setting the parameters of functions because of the orientation of computational procedures to the selected classes in terms of linguistic variables [20].

Here are the main stages of the method:

– Fuzzification of production rules, choice of membership function types, identification and formulation of membership function parameters [1];

– Solution of the problem of fuzzy logical inference Zadeh-Mamdani [14];

– Defuzzification of fuzzy logical inference by the center of mass [1];

– Determination of the estimate of the expected defuzzified value $y^{(\text{expected})}$ [14];

– Formation of parameters of the interval of values for choosing the denominator of dichotomy $d_k$, $\Delta d$, $\varepsilon$ and starting the process of iterative approximation [13];

– Stopping the process upon reaching the required accuracy $\varepsilon$ [13];

– Determination of the optimal values of the dichotomy factor $m$ for various types of membership functions;

– The conclusion of recommendations on the optimal value of the multiplier for a specific type of fuzzy value of the membership function using the ranking criterion [21];

– Rerun, clarification of the parameters of the dichotomy.

These stages do not lead to a change in the properties of the algorithm, except for introducing two parameters (the upper limit of the sampling interval for the denominator of dichotomy $d_k$, sampling step $\Delta d$). It allows you to speed up convergence if you need to select multiple parameters $k$ within a certain subject area.

We found that such an implementation has computational complexity, which is characterized by

$$O(n) \approx e^{1/\varepsilon}, \tag{13}$$

where $\varepsilon$ is a parameter of the parameter tuning method, determines the norm of the approximation accuracy.

The computational complexity of the proposed algorithm is not optimal.

When solving the problem using the method of multivalued logic [22] for some arbitrary input data, the problem of a sharp increase in computational complexity arose, this led to an unacceptably enormous increase in the program runtime. We carried modification of existing solutions out [23]. This made it possible to significantly reduce the computational complexity at the same time as increasing the stability of the work.

For each type of membership function and each divisor $d_k$, it is possible to measure the running time of the proposed algorithm $\tau_i$, where $\tau_i$ is the model time.

The solution to this problem using the methods of multivalued interval logic allows you to determine the minimum value of the model time $\tau_i$. However, in a number of cases, it is not optimal. This is because in a number of cases it is not always possible to achieve the minimum values of the model time because of the use in this approach of the value $\Delta y = | y^{(\text{actual})} - y^{(\text{expected})} | \leq \varepsilon$ as the numerator of the approximation step, which is not always adequate [13].

We defined the step denominator as $A \in (0,1), A \in R$.

In the proposed approach, the divisor is the value of the a priori given computational accuracy $\varepsilon$, which makes it possible to fulfill the condition for the model time $\tau_i$:

$$\tau_{\Delta y,A} < \tau_{\varepsilon,d}, \tag{14}$$

where $\tau_{\Delta y,A}$ is the model time when using the numerator of step $\Delta y$ and denominator $A$; $\tau_{\varepsilon,d}$ – model time using step $\varepsilon$ numerator and $d_k$ denominators.

Object-oriented modeling of implementing the stated solution is proposed (Fig. 2).

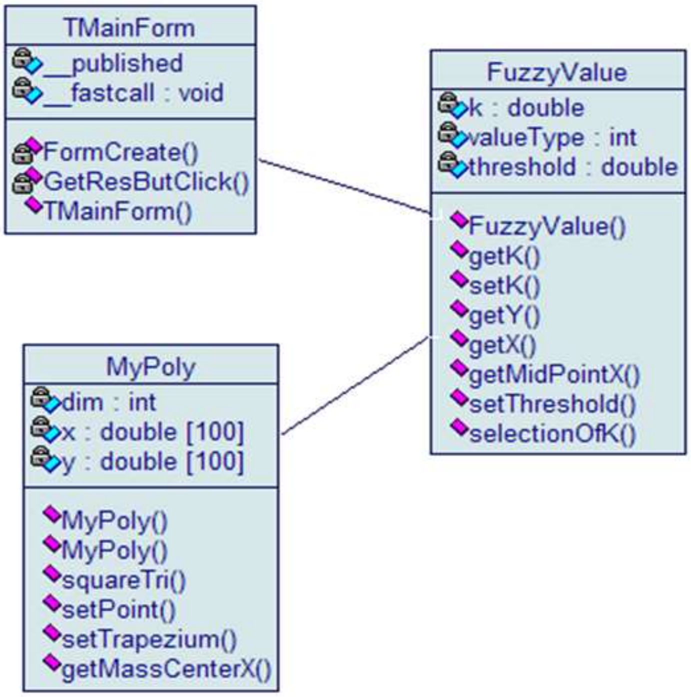


**Figure 2:** Class diagram of the developed software platform

We executed the software application in the object-oriented Python language [24]. An automated $n$-bit interval tuning of membership functions for the subject area of cardiovascular diseases has been carried out (Fig. 3, Fig. 4) [1], [13].

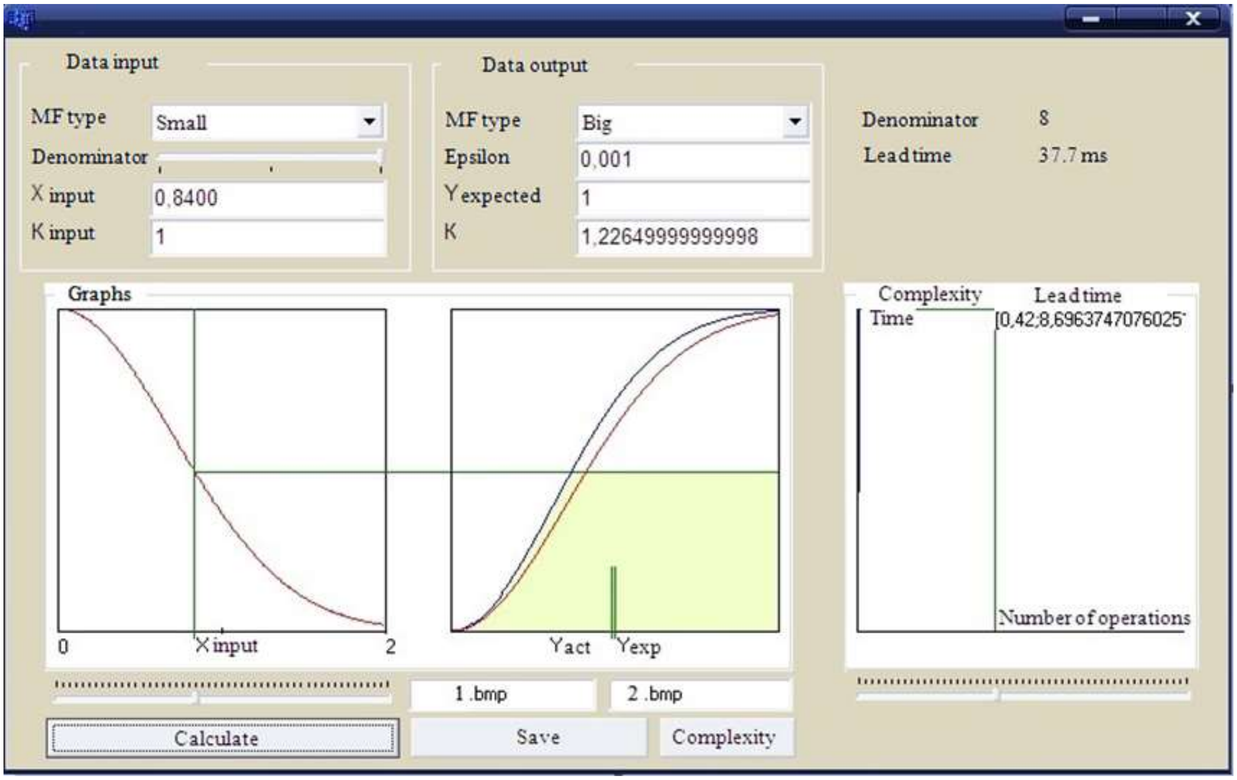


**Figure 3:** Software application interface when setting the membership function “big”

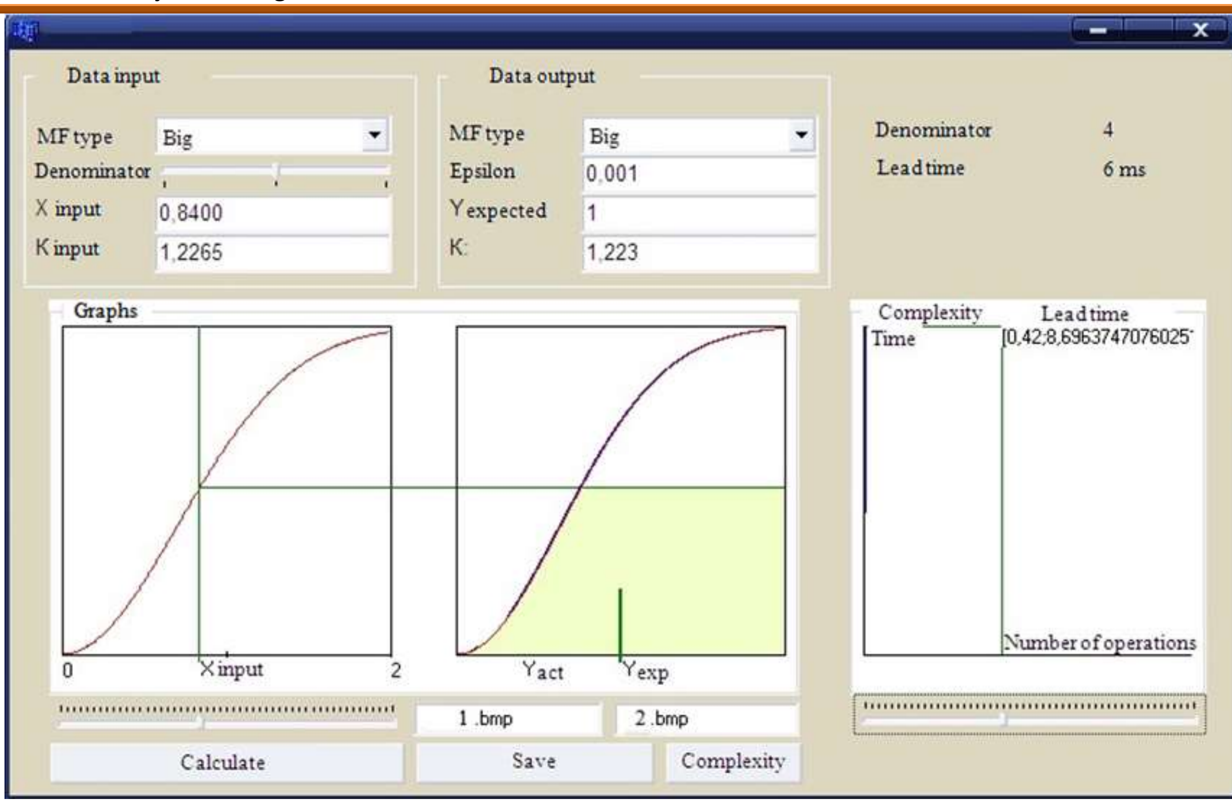


**Figure 4:** Software application interface when setting the membership function "big" (continuation)

The experiments carried out have shown the efficiency of entering the values of the divisor $d_k$ during the iterative selection process $k$ and a significant decrease in the model time $\{\tau_k\}, i \in K$ (14).

During the adjustment of the membership function, the "big" model time was reduced by 6 times, "small" – by 54 times, "medium" – 12 times with an approximation accuracy $\varepsilon$ = 0.001.

Thus, the method for tuning the parameters of membership functions based on multivalued fuzzy logic has been improved, which, in contrast to the existing ones, is based on the terms of linguistic variables and classes of membership functions with an approximation accuracy, which can significantly reduce the computational complexity of the processes.

## 5. Acknowledgment

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## 6. Conclusions

The paper developed a hybrid model and information technologies, which are the theoretical basis for the practical aspects of analyzing the states of processes in spatially distributed objects, based on evolutionary interval fuzzy models. We carried the analysis of existing approaches and methods for assessing the states of spatially distributed objects out. It is determined that the processes that can be spatially distributed in a fuzzy state space have been little studied. We concluded it is necessary to develop alternative models, methods, and information technologies for solving theoretical and practical problems.

A hybrid model is proposed, which considers the interval membership functions and algorithms for setting the membership functions of the fuzzy logical inference of Zadeh-Mamdani. Applied implementation concerns the subject areas of operational assessment of the states of spatially distributed objects, where the main criteria are accuracy and speed.

It has developed methods for making decisions about the state of objects in conditions of uncertainty, which are based on evolutionary fuzzy interval models. The method for tuning the parameters of the membership functions of fuzzy knowledge bases has been improved, which, in contrast to the existing ones, is based on multivalued interval logic.

It allows reducing the computational complexity and time of tuning the parameters of functions because of the orientation of computational procedures to the selected classes in terms of linguistic variables.

Information technology for assessing the states of spatially distributed objects has received further development, which, unlike existing ones, additionally includes models for analyzing the adequacy of constructing processes, the modification of which can significantly reduce the time spent on its implementation.

A promising area of application of the developed methods, models, and information technologies is their implementation in intelligent control tools, data processing, and knowledge processing of complex objects based on fuzzy and evolutionary algorithms.

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